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THE VISCOSITY OF SYNTHETIC TURBINE ENGINE LUBRICANTS
FROM 100° TO 700°F

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Ronald D. Butler
Midwest Research Institute

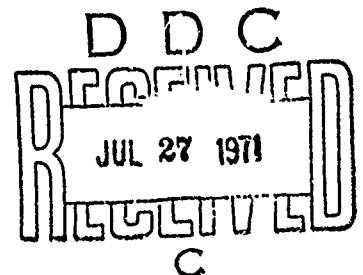
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Air Force Aero Propulsion Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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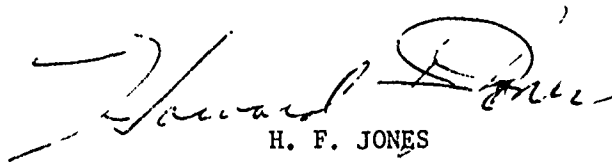
FOREWORD

This report presents results of a viscosity investigation on synthetic turbine engine lubricants. The work was performed by Midwest Research Institute, 425 Volker Boulevard, Kansas City, Missouri 64110, under Contract No. AF33615-69-C-1265, "Research for Lubricant Evaluation Techniques, Lubricant-Bearing Evaluation." The contract was initiated under Project No. 3048, "Fuels, Lubrication, and Hazards," Task No. 304806, "Aerospace Lubricants." The work was administered by the Fuels and Lubrication Division, Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The project engineers were Messrs. L. J. DeBrohun and H. A. Smith (AFAPL/SFL). This report was submitted by the author in April 1971.

The work described in this report, covering one phase of the subject contract, was performed by Messrs. S. Davis, L. Hall, G. Hampton, D. Jehn, J. Klingensmith, G. Pelcher, and T. Stein, under the supervision of Dr. Ronald D. Butler. The on-site project manager is Webster D. Wood and the principal investigator for the program is Vern Hopkins.

Grateful acknowledgment is given to Dr. R. F. Manning, Cannon Instrument Company, for numerous helpful suggestions regarding the experimental technique described in this report. Valuable technical advice and assistance was also provided by Messrs. G. A. Beane and J. B. Schrand, U. S. Air Force Aero Propulsion Laboratory.

This technical report has been reviewed and is approved.



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Chief, Lubrication Branch
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ABSTRACT

This report describes a technique for the experimental determination of fluid viscosity over the temperature range 100°-700°F. The method incorporates standard procedures, and meets accepted specifications for data precision and for temperature control and measurement over the entire temperature range. Reliable data of high precision can be obtained for subsequent analysis and prediction of lubricant performance in operating turbine aircraft engines.

Complete viscosity data are presented for 30 synthetic lubricants. The following fluid types were included in this study: MIL-L-7808, MIL-L-23699, MIL-L-27502, poly(phenyl ether), and silicone formulations. Statistical analysis of the data indicates that the relationship

$$\log_e \nu = A + B \log_e t + C/t$$

accurately describes the variation of kinematic viscosity with temperature over the entire temperature range. This equation can be used to calculate fluid viscosity at any desired temperature up to 500°F (or 700°F for thermally stable lubricants) with an average error less than 2%.

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I.

INTRODUCTION

The viscosity of a fluid lubricant has long been recognized as its single most important mechanical property from the standpoint of its performance in an engine. Viscosity is of particular interest because it determines oil flow rates through a lubrication system and over moving parts. Viscosity is also an important factor in the load-carrying capability of lubricants. An engine lubrication system must be designed to deliver lubricant at each point in the engine requiring lubrication and frequently cooling at a specified flow rate. Consequently, viscosity must always be considered in the selection of a lubricant for use in an existing propulsion system, in order that the proper delivery rate can be obtained.

Techniques for determining fluid viscosity experimentally are well established, and it is possible to obtain very precise and reproducible data under closely controlled conditions. Viscosity values are usually reported at certain conventional temperatures, such as 20°C, 25°C, 100°F, 130°F, 210°F, and 100°C. These particular temperatures have become accepted as standard over a period of years, mainly because of tradition but also as a matter of convenience. It is not common practice to measure and report viscosity data above 210°F, although there does exist a genuine need for good viscosity data for fluid lubricants at elevated temperatures. Current turbine engines typically operate with the bulk oil temperature reaching 300-400°F, and the oil is exposed to much higher temperatures in the pumps, seals and bearings of the turbine section of the engine. In advanced propulsion systems--those capable of producing speeds in excess of Mach 3--these temperatures are expected to be as high as 700-800°F. Analysis of the operating characteristics of the engine requires a good estimate of lubricant flow properties under the conditions actually encountered in the engine. It is therefore highly desirable to have available a technique for determining fluid viscosities at temperatures up to 700°F.

Usually, data up to 210°F are plotted on viscosity-temperature charts such as those published by the American Society for Testing and Materials, and estimates of viscosity at higher temperatures are obtained by linear extrapolation. The scales on these charts are generated from complex functions based upon empirical relationships, and do give linear plots for certain classes of fluids. However, it is widely known that the linear portions of these plots cannot be extrapolated with confidence to give viscosity values at higher temperatures; as a rule, the experimental data begin to deviate from the extrapolated values above about 300°F, and the

deviations increase with increasing temperature. For this reason, at present the only reliable means for obtaining valid viscosity data above 300°F is to make the determinations experimentally.

This report describes a technique that has been developed on behalf of the U. S. Air Force Aero Propulsion Laboratory for determining lubricant viscosity values at high temperatures. Measurements have been made on a number of fluids up to 500°F, at which temperature most conventional lubricants undergo extensive thermal degradation and the experimental data begin to lose their significance. Several experimental fluids having greater thermal stability have, however, been studied up to 700°F. The experimental apparatus and the results are described herein.

II.

EXPERIMENTAL METHODS: TEST REQUIREMENTS AND PROCEDURES

All procedures and measurements made in this work conform to the specifications established by the American Society for Testing and Materials, as described in ASTM Method D445, "Test for Kinematic Viscosity" (Ref. 1). At 100°F and 210°F, this standard specifies that the difference between duplicate viscosity determinations made by the same operator should be less than 0.35% of their mean value; results reported by two different laboratories, assuming sound technique on the part of both, should not differ by more than 0.70% of their mean value.

Temperature is the most important experimental parameter in viscosity measurements, and requires very precise control. For many fluid lubricants, the variation of viscosity with temperature may be as great as 3% per °F near 100°F. This means that at 100°F, the temperature must be controlled at least to within $\pm 0.1^\circ$ in order to ensure that the results will be within the 0.35% repeatability limit. Since other factors also influence repeatability, temperature control must be much better than $\pm 0.1^\circ$; it is generally agreed that control to within $\pm 0.03^\circ\text{F}$ is reasonable for viscometry work, and this tolerance has been adopted for all of the determinations described in this report.

A. Temperature Measurement

Not only must temperature be controlled to conform to close tolerances, it is also necessary to obtain precise measurements of the actual working temperatures. Therefore, all thermometers used must be calibrated so that the temperature can be measured to an accuracy of $\pm 0.03^\circ\text{F}$ or better.

For most of the work reported here, temperatures were measured using carefully calibrated platinum resistance thermometers. Two such thermometers (Leeds & Northrup Models 8160-B and 8163-C) were calibrated by the Air Force Measurement Standards Laboratory and certified to be accurate to within $\pm 0.01^\circ\text{C}$ ($\pm 0.018^\circ\text{F}$). The calibrations are based upon the International Practical Temperature Scale of 1948 (IPTS-48), and for the resistance thermometers used here are valid to 750°F. Resistance measurements were made with a calibrated Leeds & Northrup Type G-2 Mueller Bridge having a precision of ± 0.0001 ohm. Temperatures were computed from resistance measurements by means of an interpolation program provided with the thermometer calibrations and based upon the modified Callendar-Van Dusen equation for temperatures above 0°C,

$$R_t/R_0 = 1 + \alpha t + \alpha \delta (t \times 10^{-2}) - \alpha \delta (t^2 \times 10^{-4}) ,$$

where R_t is the resistance of the thermometer element at temperature t , R_0 is the resistance at 0°C , and α and δ are constants characteristic of the individual thermometer. The precision of this method is such that temperatures computed using the reported calibrations are accurate to within $\pm 0.02^\circ\text{F}$.

Periodic checks were made on the resistance thermometers by measuring their resistance values at the triple point of water. This temperature, which has been defined as 0.010°C precisely, was achieved by means of a triple-point-of water cell manufactured by Trans-Sonics, Inc., Burlington, Massachusetts. The reference resistance at 0°C was computed by dividing the value measured at the triple point by the known factor of 1.0000398 for platinum. These periodic checks revealed that R_0 , the resistance of the thermometer element at 0°C , varies less than 0.001% over a 6-month period. This drift is well within the certified accuracy of the thermometer and was considered negligible.

Ordinary mercury-in-glass thermometers were also used for monitoring the working temperatures when determinations were made in conventional fluid constant-temperature baths. These thermometers are designed for viscosity work (ASTM Type 28F, range 97.5 - 102.5°F ; and Type 30F, range 207.5 - 212.5°F), and are graduated in 0.1°F divisions. Although the thermometers were certified by the manufacturers to meet ASTM specifications, they were checked against the platinum resistance thermometer readings and in most cases were found to require corrections greater than 0.03°F . At least two mercury-in-glass thermometers were used together for monitoring fluid bath temperatures. This precaution also provided assurance that the temperature of the stirred bath was uniform throughout; in no case was a measurable temperature gradient detected in the fluid baths.

B. Viscosity Determinations

All viscosity measurements were made by the standard technique of timing the fluid flow past two points in a capillary viscometer. The viscometers used here were of the Cannon-Fenske and Cannon-Ubbelohde types manufactured by Cannon Instrument Company, State College, Pennsylvania. These viscometers were supplied with certificates of calibration, and conform to specifications of the National Bureau of Standards. In order to ensure that the calibrations were valid over long periods of use, they were checked periodically against standard viscosity fluids also available through Cannon Instrument Company and certified under the ASTM Cooperative Viscosity Program. Only slight changes, indicating a need for more thorough cleaning from time to time, were observed.

Cannon-Ubbelohde viscometers were selected as the preferred instruments for most of this work. These viscometers have two important advantages over other types, which more than compensate for their slightly higher cost. First, their design provides a constant fluid driving head, so that the efflux time is not sensitive to the sample size taken, unlike the Cannon-Fenske design, in which the sample volume is critical. Second, the calibration of the Cannon-Ubbelohde viscometer is independent of temperature, again in contrast to other types, so that no corrections or conversions are required when working at temperatures other than those at which the viscometer was calibrated.

Kinematic viscosity values were determined by carefully timing the flow of the fluid sample past two marks on the viscometer and multiplying the measured times by the certified viscometer constant:

$$\nu = k\tau$$

where ν is the kinematic viscosity in centistokes, k is the viscometer constant, and τ is the measured time in seconds.

Mechanical stopwatches were used for timing purposes. All of the timers were calibrated against the time signals broadcast by the National Bureau of Standards over Station WWV, Fort Collins, Colorado. In every case, the watches were found to be accurate to well within $\pm 0.01\%$.

C. Apparatus: Measurements Below 300°F

For most work below 300°F, commercially available viscometry equipment was found to be satisfactory. Constant-temperature viscosity baths manufactured by Cannon Instrument Company (Model H-1) were used for controlling temperature up to 300°F. These units have exhibited excellent control, uniformity, and stability; at any preset temperature within the range 100-300°F, the maximum variation was less than $\pm 0.02^\circ\text{F}$, which is well within the control tolerances described above. As noted above, we were unable to detect any temperature gradients within these baths. Water was the most suitable bath medium up to about 140°F; stabilized bath oils, such as that available through Fisher Scientific Company, can be used above this temperature, and are suitable for intermittent use between 250° and 300°F.

III.

VISCOSITY DETERMINATIONS FROM 300° TO 700°F

In the foregoing discussion it was pointed out that fluid viscosity determinations can be made more or less routinely up to 300°F utilizing commercially available equipment. Above 300°F, however, difficulties arise that make the use of fluid baths impractical. Obviously, heat losses at higher operating temperatures can be severe enough to result in poor temperature control. A more serious problem associated with fluid baths is the lack of fluids that are suitable for use at high temperatures.

The familiar mineral oil formulations, even those containing oxidation inhibitors, tend to darken and smoke excessively above 250°F, so that their useful life can be quite short. It is true that some silicones are serviceable to 500°F and higher, but they have serious disadvantages. They are, for example, notorious for their tendency to contaminate glassware; they may contaminate the walls of a viscometer capillary, thereby changing the viscometer constant, and they are extremely difficult to remove. Silicones should therefore be avoided in viscometry work (Ref. 2). Other synthetic fluids, such as poly(phenyl ether) and fluorinated polymers, are impractical because of their high cost. Molten inorganic salt mixtures have been used as bath media, but these mixtures usually contain nitrates and can become explosive if not handled properly. It has been suggested that air itself would make a satisfactory bath medium. However, we were unable to locate a source of well-insulated ovens having both an extended temperature range (to 700°F) and good temperature control capability (better than 0.1°F).

The objective of this work has been the development of a technique that would circumvent these difficulties and still provide adequate temperature control for viscosity measurements up to 700°F. One such method has been reported by Awwad in collaboration with Cannon Instrument Company (Ref. 3). This procedure takes advantage of the fact that the vapors above a boiling liquid can serve as an efficient constant-temperature medium provided the pressure of the system is held constant and the refluxing liquid does not decompose.

An apparatus has been constructed on this principle for determining fluid viscosities over an extended temperature range. This equipment is patterned after the prototype used by Awwad. The overall facility is shown in Figures 1 and 2. It consists essentially of a modified capillary viscometer, a heat source, a vacuum system, a pressure control system, a temperature-measuring system, the refluxing liquid, and support facilities.

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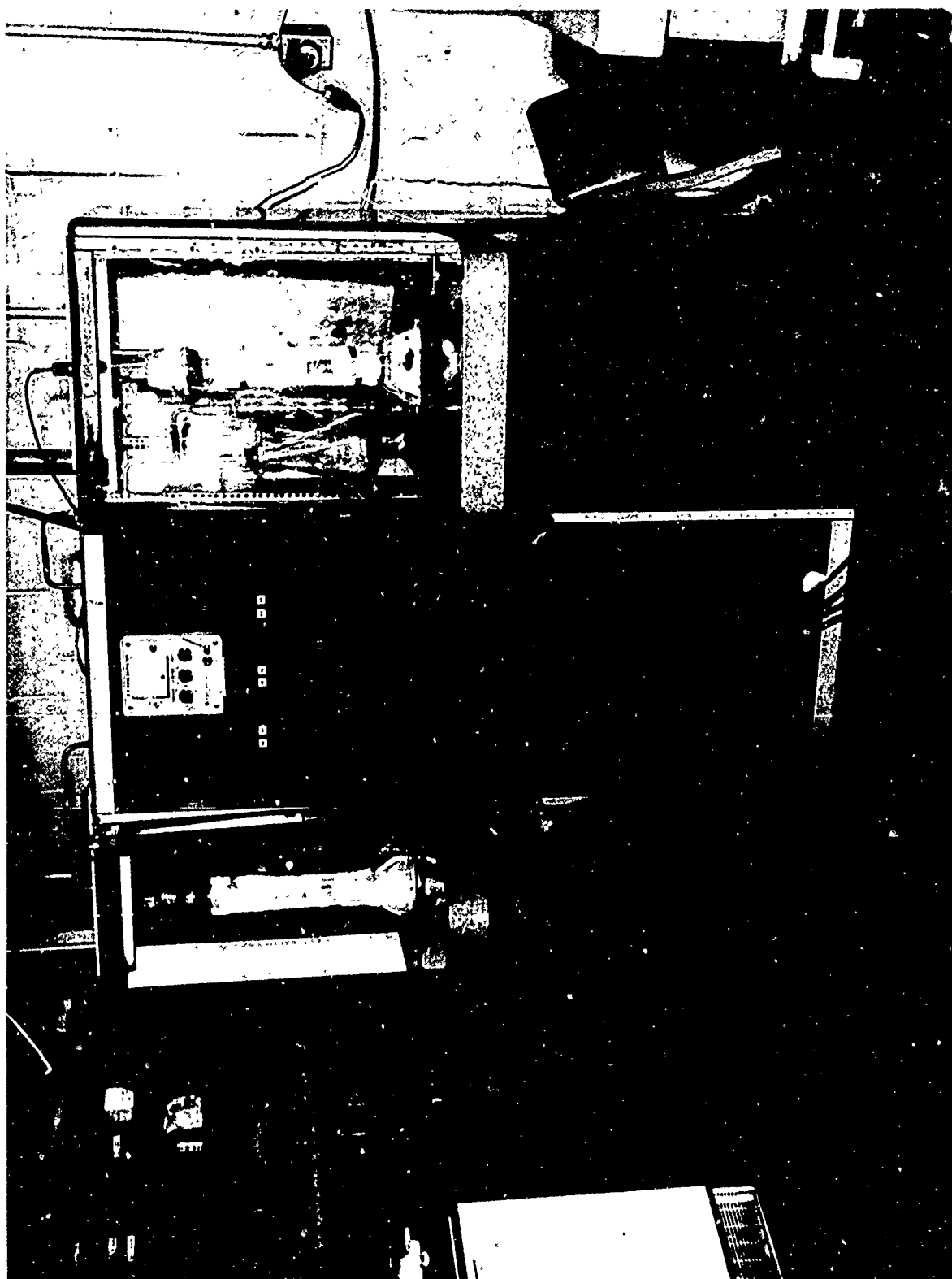


Figure 1 - High-Temperature Viscometry Facility

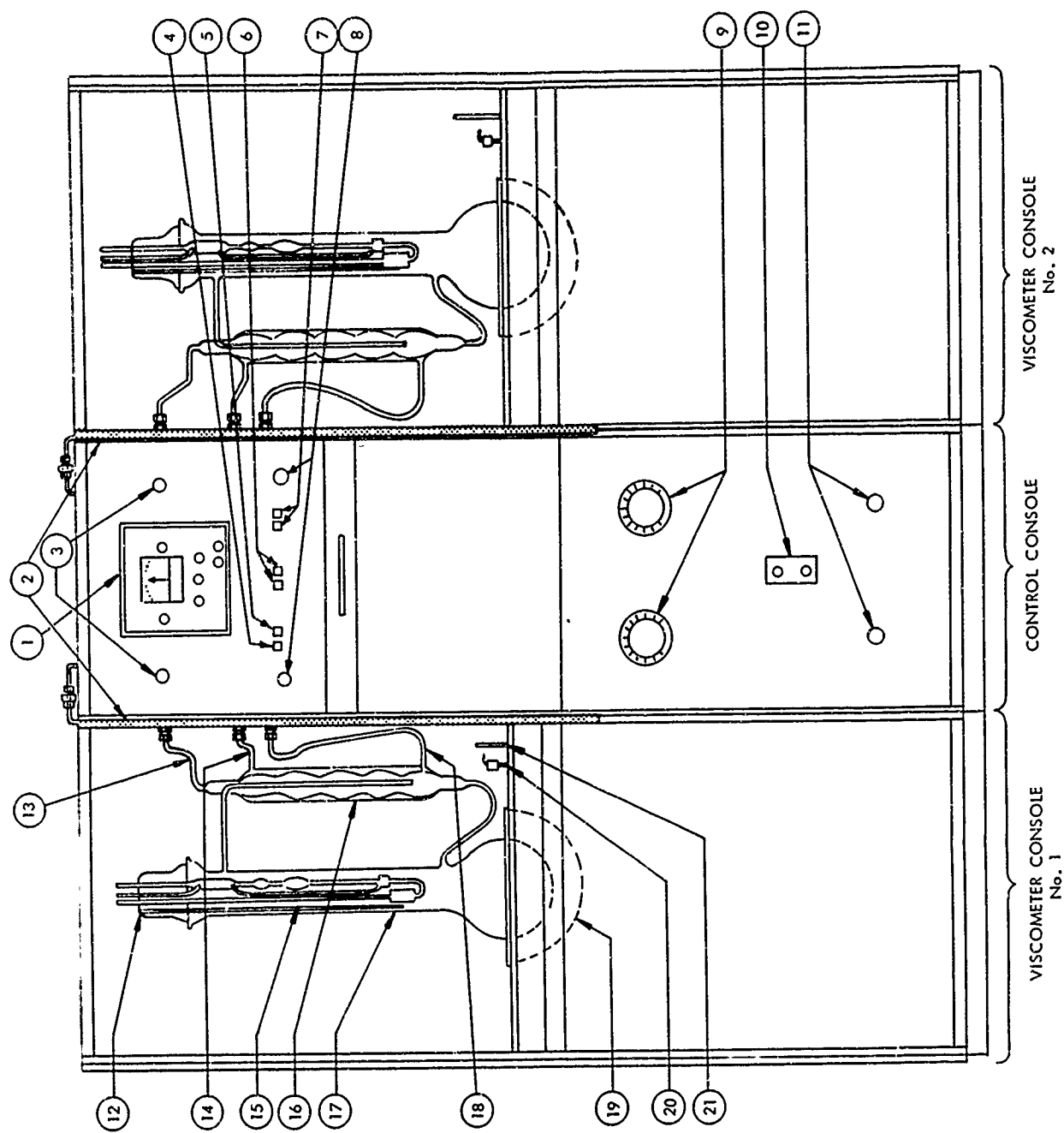


Figure 2 - Schematic of High-Temperature Viscometer Control Console

- 1 D.C. Null Detector
- 2 Manometer
- 3 Vacuum Bleed Valve
- 4 Main A.C. Power Switch
- 5 Vacuum Pump Switch
- 6 Solenoid Valve Switch
- 7 Heating Mantle Switch
- 8 Vacuum Control Valve
- 9 Variable Transformer
- 10 110 v. A.C. Outlet
- 11 Water Valve
- 12 Thermometer Well
- 13 Vacuum Line
- 14 Water Outlet
- 15 Modified Cannon-Ubbelohde Viscosity Tube
- 16 Condenser
- 17 Reflux Flask
- 18 Water Inlet
- 19 Heating Mantle
- 20 Vacuum Valve
- 21 House Vacuum

The viscometry facility, as shown in Figure 1, incorporates two separate viscometer assemblies, which share a common control console. This design was followed because of the minor additional cost of constructing a double, rather than just a single, unit. Furthermore, each unit may be used to cover a different temperature range, thus eliminating the need for changing over a single unit when conducting tests over different temperature ranges. In the following description, the details refer to the design and operation of a single unit; since both units are identical, it may be inferred that the principles outlined here apply to both units.

A. Viscometer Assembly

The viscosity-measurement apparatus itself consists of the modified Cannon-Ubbelohde capillary viscometer shown in Figure 3. The modification provides a means of suspending the viscometer in the vapor bath using a standard 75/50 ball-and-socket joint. This joint is sealed with Apiezon Type H vacuum grease, which is the only material found that is capable of maintaining a tight seal, over the full range of operating temperatures.

The boiler chamber is fabricated from a section of a 1-liter round-bottom flask sealed onto 50-mm. Pyrex tubing; this section of the viscometer assembly contains the refluxing fluid for controlling temperature, and fits into a standard electric heating mantle. The condenser section shown in Figure 3 serves to liquefy and return the vapors to the boiler section, so that nearly total reflux is achieved. The side arm at the top of the condenser section leads to the vacuum and pressure-regulation system. In use, the entire viscometer assembly is encased in preformed heat-curing ceramic insulation supplied by Refractory Products Company, Evanston, Illinois.

B. Heat Source

A steady source of heat for the boiler is provided by a high-temperature heating mantle, as indicated in Figure 2. The mantle used here, Glas-Col Apparatus Company Model 146175, is rated at 600 W, has quartz insulation, and has a nominal maximum operating temperature of 650°C (1200°F). The mantle is recessed into a hole cut into the supporting shelf, and is attached by means of mounting screws in the metal rim of the mantle. Power input to the mantle is controlled manually by means of the variable transformer (Statco Type 751, 0-140 V) located on the central console panel.

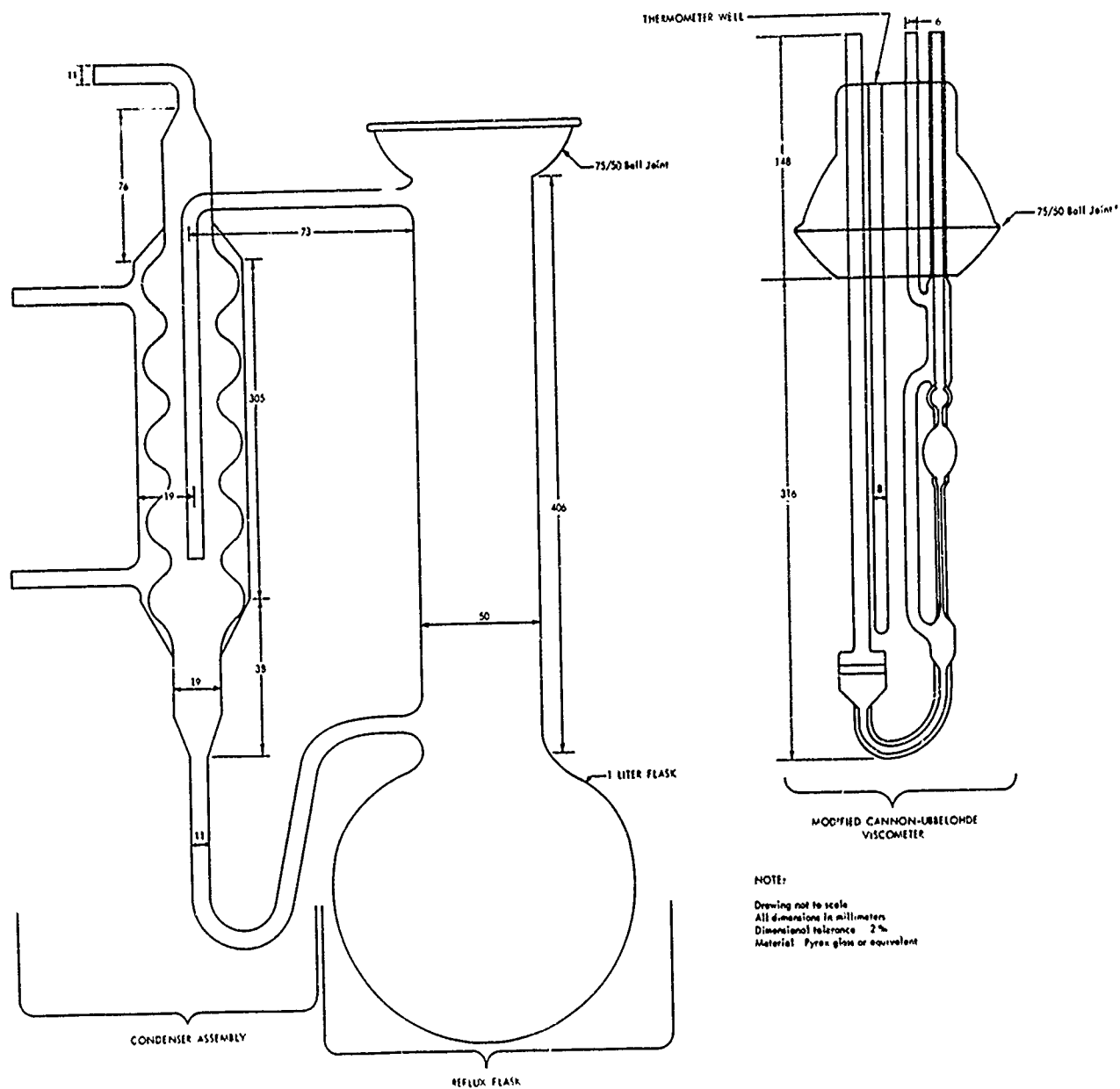


Figure 3 - Vapor-Bath Viscometer Assembly

C. Vacuum System

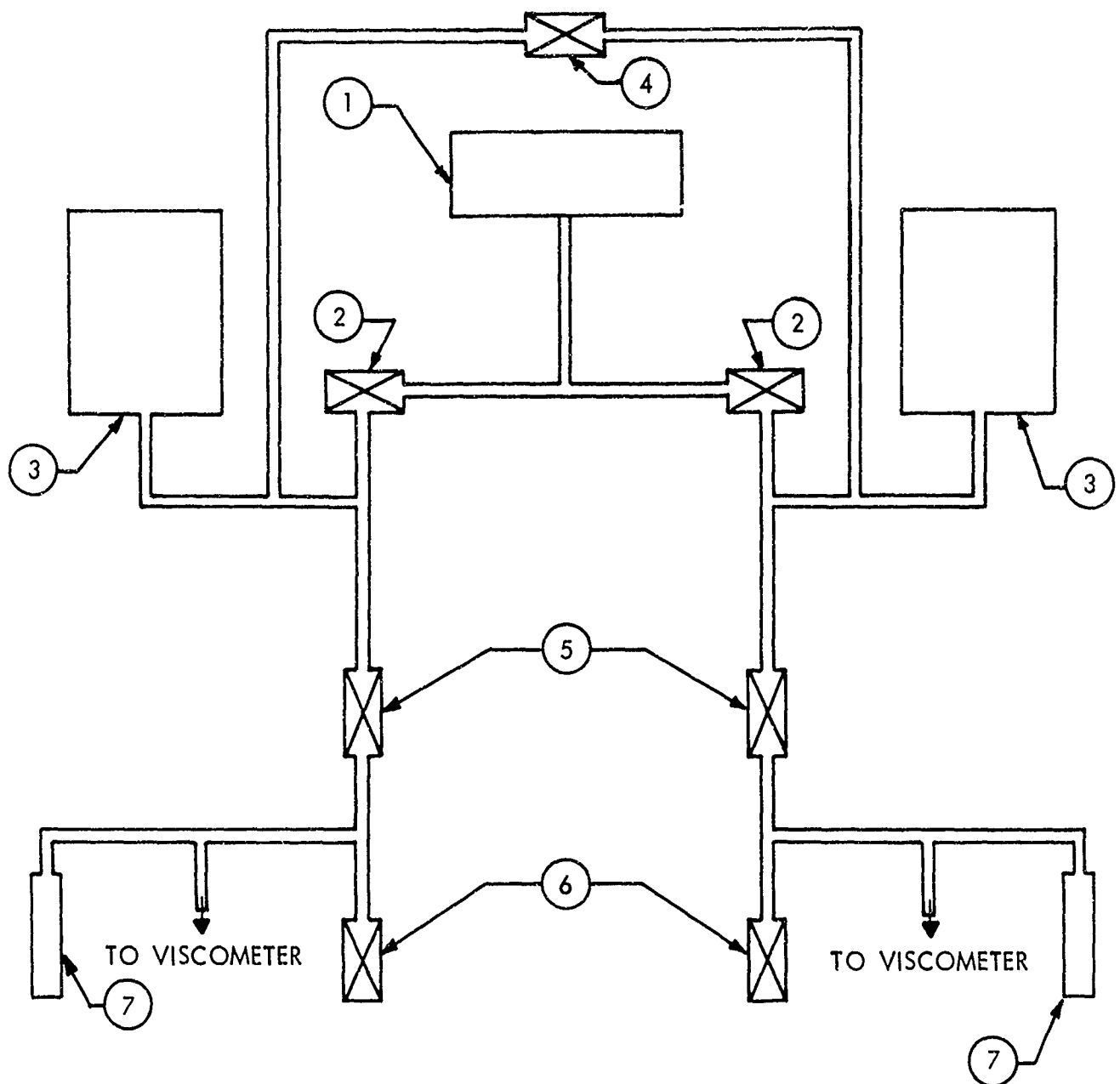
The boiling temperature of the refluxing liquid is determined by the pressure in the system. Within limits, a particular steady temperature below the normal boiling point of the liquid can be attained merely by maintaining a constant reduced pressure. The vacuum system shown schematically in Figure 4 makes provision for pressure variation, and thereby temperature selection. Reduced pressure is provided by a Duo-Seal vacuum pump (W. M. Welch Manufacturing Company). All vacuum lines were constructed of 1/4-in. copper or heavy wall Tygon tubing. The various valves indicated in Figure 4 are stainless steel needle valves (Hoke, Inc.).

D. Pressure Control

Pressure in the system is continuously variable from 50 to 760 mm. Hg, and can be automatically controlled at any point within this range. The principle employed here is identical to that used in the familiar mercury-contact thermoregulator. The system is shown schematically in Figure 5. Mercury in the closed side of a U-tube manometer makes continuous electrical contact with a relay by means of a fixed copper lead. The manometer used here is constructed so that the mercury is in direct contact with the bottom of the metal case; therefore, it is convenient to connect the relay lead directly to a metal fitting on the manometer case.

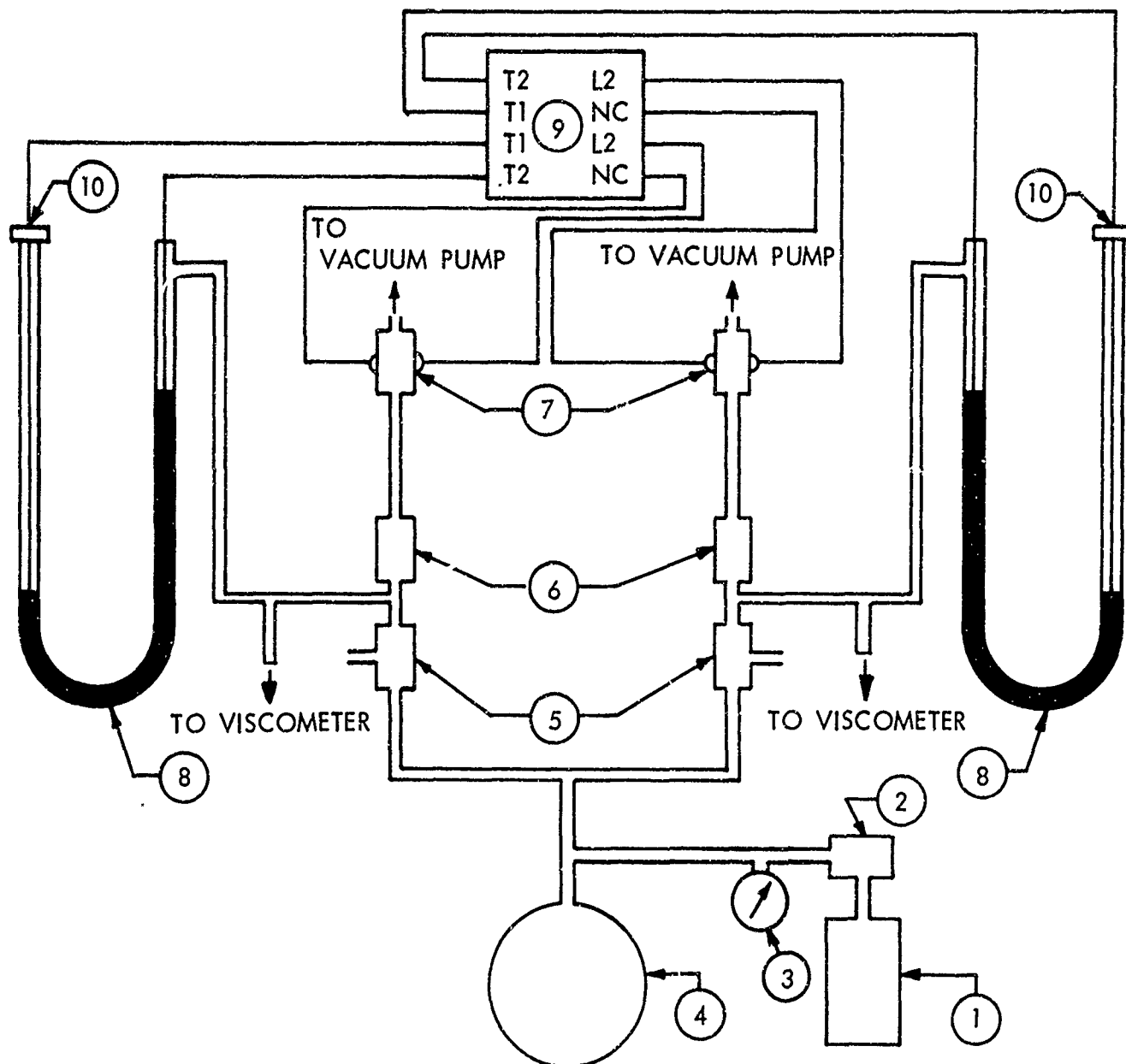
A metal probe made of 1/16-in. stainless steel rod extends into the open arm of the manometer and is electrically insulated from the case by means of a Nylon lock nut. The probe is manually adjusted up or down to extend any desired distance into the open side of the manometer, corresponding to the required difference in height of the mercury levels in the two arms. A second electrical lead connects the probe to the relay. Thus, a complete circuit is made when the tip of the probe contacts the mercury in the open arm of the manometer. Connections to the relay are shown in the relay circuit diagram in Figure 6. If the pressure in the system is higher than required, the probe extends into the mercury column. This completes the circuit, and the relay signals the solenoid valve to open the system to the vacuum pump. As soon as the pressure is reduced to the control point, the probe breaks contact with the mercury and the solenoid valve closes.

The remaining components shown in Figure 5 are provided for fine control. The ballast tank is a 1.2 cu. ft. aviation oxygen tank, which serves to prevent sudden pressure fluctuations when the solenoid valve opens the system to the action of the vacuum pump. A manually adjusted needle valve in the vacuum line also controls the rate at which pressure is reduced in the system.



- 1 Vacuum Pump
- 2 Solenoid Valve
- 3 Ballast Tank
- 4 Crossover Valve
- 5 Vacuum Control Valve
- 6 Bleed Valve
- 7 Manometer

Figure 4 - Schematic of Vacuum System for High-Temperature Viscometer Facility



- | | |
|----------------------|------------------------------------|
| 1 Nitrogen Source | 6 Vacuum Control Valve |
| 2 Pressure Regulator | 7 Solenoid Valve |
| 3 Pressure Gage | 8 Manometer |
| 4 Ballast Tank | 9 Relay (See Figure 6 for Details) |
| 5 Bleed Valve | 10 Adjustable Probe |

Figure 5 - Schematic of Pressure Control System for High-Temperature Viscometer Facility

Power Transformer: Primary 115 v., 60 Hz; Secondary 115 v., 60 Hz, 15 ma; Filament 6.3 v., 0.6 amp.
Relay: Sigma 41ROZ - 10,000 ACS SIL
Tube: 2D21
Resistors: R1, 10 k Ω , 1 w.; R2, 1 M Ω , 1/4 w.; R3, 39 K Ω , 1/4 w.
Capacitors: C1, 0.1 μ F, 200 WVDC; C2, 5 μ F, 50 WVDC.
Diode: CR, 1N34.

Figure 6 - Circuit Diagram for Pressure Control Relay

A second needle valve is used for admitting either air or nitrogen to the system at a slow, controlled rate; this feature serves further to smooth out pressure fluctuations, and also prevents excessive carryover of vapors of the refluxing liquid into the vacuum lines.

This pressure-control system has proven to be quite successful. With proper manual adjustment of the vacuum and air valves, it is possible to maintain a pressure that is constant to within ± 1 mm. Hg. For the fluids that have been used for controlling temperature, this pressure variation corresponds to a maximum temperature fluctuation of $\pm 0.03^\circ\text{F}$ at most temperatures.

E. Temperature Measurement

A thermometer well is incorporated into the design of the modified viscometer (see Figure 3) to accommodate a platinum resistance thermometer. A small amount of thermally stable fluid, such as a silicone or poly(phenyl ether), is placed in the thermometer well to cover the platinum sensing element. Good temperature measurement is achieved by this placement of the sensing element near the test fluid in the viscometer.

F. Vapor Bath Medium

As stated above, the boiling temperature of a fluid can be depressed below its normal boiling point by reducing the pressure of the atmosphere above the liquid. For most organic liquids, the boiling point can typically be lowered some $140\text{--}160^\circ\text{F}$ by operating at a pressure of 50 mm. Hg, the lowest practicable working pressure in our system. Thus, by varying the pressure in the system it is possible to control the boiling point, and thereby the test temperature, at any temperature over a range of about 150°F with a single refluxing fluid.

This interval for a single refluxing liquid is not sufficient to cover the entire range of interest ($300\text{--}700^\circ\text{F}$). It is therefore necessary to use a series of different liquids, preferably having overlapping temperature ranges, to achieve all of the desired operating temperatures. The choice of organic materials for this purpose would seem to be almost unlimited, but such is not the case. Safety considerations require that the materials be as nearly innocuous as possible, since some fumes do invariably escape through the vacuum pump and may be vented to the laboratory. Likewise, the substances must not be corrosive or otherwise deleterious to the vacuum lines and valves. Finally, the materials must be stable and pure enough to allow a constant boiling temperature.

Shown in Figure 7 are the useful boiling-temperature ranges for several organic materials that have been found to meet these criteria. Depending upon the temperature desired, there is some flexibility in the choice of reflux fluids, particularly between 200° and 350°F. At the highest temperatures, the choice is severely limited; only m-terphenyl, of seven suggested materials evaluated, was found to have the desired qualities of thermal stability, constant boiling temperature, and upper temperature capability of 700°F.

The compounds found to be most useful and successful for temperature control above 300°F are diphenyl ether (range 320-495°F) and m-terphenyl (550-700°F). These two materials provide a capability for maintaining and controlling nearly any temperature between 320° and 700°F.

G. Support Facilities

All of the components discussed above were assembled and installed in standard enclosures. Placement of the various components was a matter of operator convenience, and no specific recommendations are made with regard to the construction of similar units.

Shown in Figure 8 is an electrical wiring diagram for the viscometer facility. The electrical service is 100 V AC with a current rating of 30 amps. Fuses are located inside the console for the protection of the various components; the ratings of these fuses are indicated in Figure 8. The main console power switch and individual power switches to the components are located on the front control panel, as shown in Figure 2. For convenience, a double receptacle is placed on the front of the console to provide auxiliary power for appliances such as lights and timers.

Cooling water for the condenser is supplied from a line entering through the rear of the center console and extending to the shelf supporting the glass viscometer assembly. Valves mounted on the front control panel (see Figure 2) control the water flow rate. A return line from the condenser provides discharge into a waste water drain.

An auxiliary valve mounted conveniently on the support shelf in the end cabinet unit provides house vacuum service. This vacuum line aids in drawing test fluid up into the viscometer and in cleaning the viscometer assembly after a test. Not indicated in the accompanying figures is a waste trap, which consists of a 5-gal. carboy in the house vacuum line for collecting waste fluids.

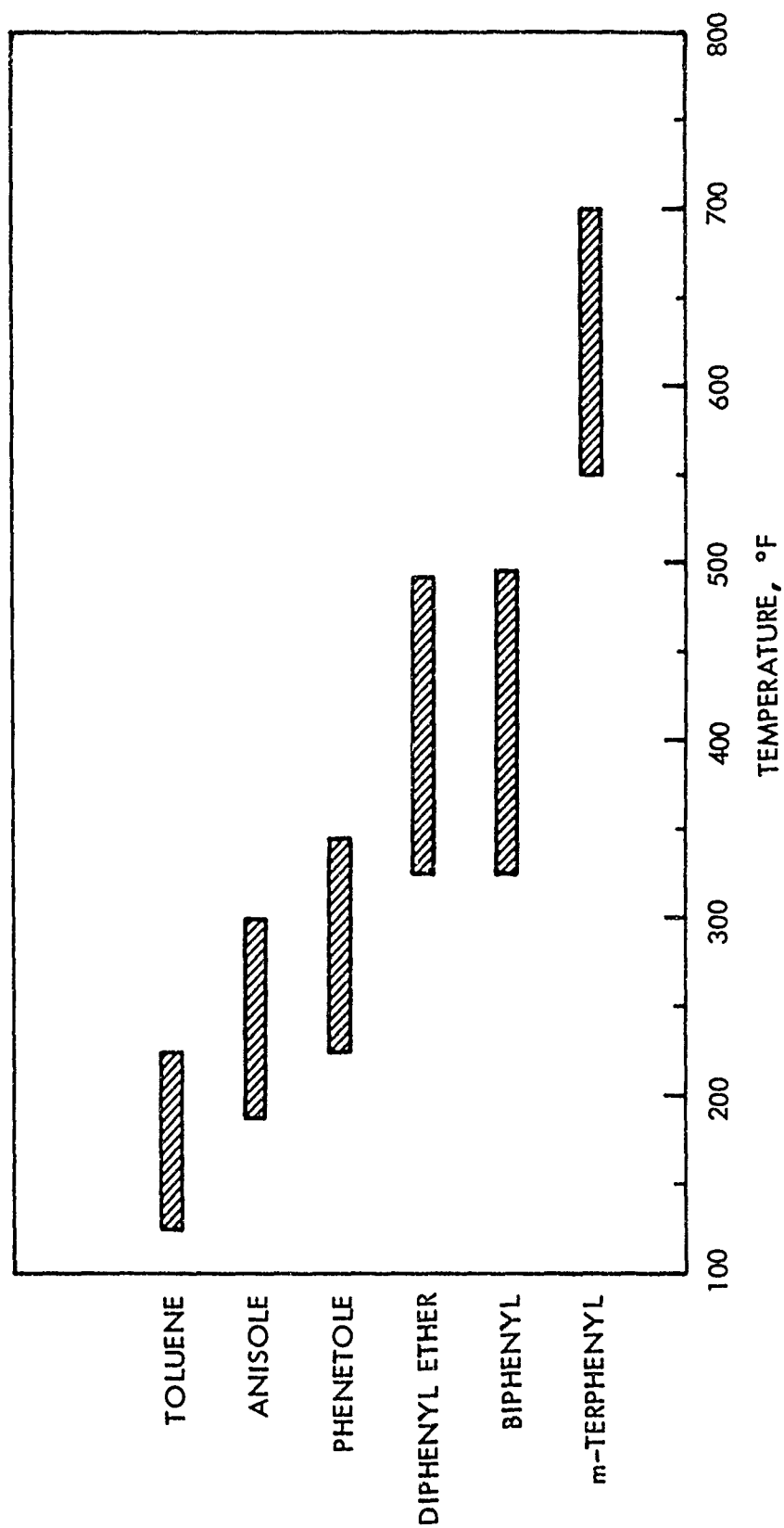


Figure 7 - Practical Temperature Ranges of Fluids Used for Temperature Control in High-Temperature Viscometer

H. Operating Procedure

Approximately 200 gm. of the vapor bath material (phenyl ether, m-terphenyl, etc.) is charged into the boiler flask and the flask is placed in the heating mantle and connected to the vacuum line. The ball joint is thoroughly coated with Apiezon vacuum grease, and the modified viscometer is fitted in place. The joint is rotated and rocked with slight pressure to ensure a uniform seal. If desired, the viscometer can be clamped in a true vertical position by hanging a plumb weight inside the filling tube, as described in ASTM Method D445. The plumb line is removed and test oil is introduced through the filling tube until the level reaches the fill mark on the viscometer reservoir. The viscometer assembly is encased in preformed insulation and clamped into position. The thermometer well is filled about one-third with a high-temperature fluid, and the resistance thermometer is inserted and connected to the Mueller resistance bridge. Connections are made from the bridge to the null detector and the null detector is turned on.

The air and vacuum valves on the front console are shut off and the power switches are turned on to activate the vacuum pump, heating mantle, and relay-solenoid control. The manometer probe is inserted into the mercury column to a depth corresponding to a difference of about 28 in. (712 mm. Hg) in the heights of the two mercury columns. This setting provides an initial system operating pressure of approximately 50 mm. Hg. The vacuum valve is opened gradually to permit evacuation of the viscometer jacket. As soon as the pressure is reduced to the control point, the air bleed valve is opened gradually to admit a slow stream of air and thereby prevent pumping past the control point. The rate of evacuation and introduction of air are adjusted manually by means of the vacuum and air valves until stable control is reached; at this point the relay cycles every few seconds, and with the valves properly adjusted the mercury level in the manometer remains nearly constant without bumping appreciably when the solenoid valve opens and closes.

Power input to the heating mantle is controlled by manual adjustment of the variable transformer until stable boiling is reached with a steady carryover of vapors into the condenser section. A slow stream of water is run through the condenser to provide nearly complete condensation and return of the vapors to the boiler section. (Caution: Cooling water is not advised when operating with a high-melting material such as m-terphenyl, as this results in solidification and blockage inside the vapor-return tube. With such materials, it is preferable to maintain the condenser at a temperature of about 200°F by wrapping the condenser with heating tape or by passing steam through the condenser jacket.)

The temperature of the viscometer chamber is monitored by means of the resistance thermometer until it is constant to within about 0.01°C (for most platinum sensing elements, this corresponds to a resistance variation of about $\pm 0.0010 \Omega$). The test fluid is drawn up into the upper reservoir of the viscometer and allowed to run through once in order to ensure that it has reached a uniform temperature. The viscosity measurement is then made in the customary manner, by timing the fluid flow past the two marks on the viscometer. At least three measurements are made, and their mean value is acceptable if the temperature remains constant to within $\pm 0.03^{\circ}\text{F}$ during the test and the spread of the individual results is less than 0.35% of the mean value.

The temperature is then increased for the next set of measurements by raising the metal manometer probe and allowing the pressure in the system to rise to the new control point. The vacuum and air valves are again adjusted manually to give a stable pressure, and if necessary the power input to the heating mantle is increased to maintain steady boiling. A new set of viscosity measurements is made after a constant temperature has been established, and the procedure is repeated until the temperature range of interest has been covered.

Depending upon the temperature capability and volatility of the fluid being tested, a number of viscosity determinations can be made at several temperatures without changing the sample. Some degradation is often evidenced by darkening of the sample, but the change does not seem to be great enough to affect the viscosity values. When substantial degradation does occur, the viscosity measurements become erratic and the test is terminated. If desired, the apparatus can be cooled to room temperature, cleaned, and charged with fresh sample in order to perform immediate measurements at the higher temperatures where breakdown has been suspected.

The viscometer assembly is designed so that it can be cleaned in place without disassembly. After cooling to room temperature, the test fluid is drawn out into a waste chamber in the house vacuum system, and the glassware is cleaned by thoroughly purging several times with Freon-113, acetone, and reagent grade methanol or 2-propanol. Residual stains can usually be removed by allowing a mixture of 50% 2-propanol, 45% toluene, and 5% water to stand in the assembly overnight. For intransigent residues, the modified viscometer section is removed and cleaned with chromic acid or hot nitric acid. (WARNING: These cleaning agents are powerful oxidants and must be used with extreme caution; all traces of organic solvents must be removed before they are used, and the glassware should be flushed with copious quantities of hot distilled water after cleaning.)

IV.

FLUID VISCOSITY DATA, 100° TO 700°F

A. Materials Studied

Two reference fluids and 30 synthetic turbine engine lubricants have been tested in this program. A description of these fluids is given in Table I, together with the highest temperatures at which they were studied and their kinematic viscosities at 100°F.

The test fluids cover a variety of lubricants, and include most of the formulations either proposed or currently in use by the U. S. Air Force: MIL-L-7808, MIL-L-27502, MIL-L-23699, experimental ethers, and one silicone. In one case, a single fluid was tested under two different code numbers; and several samples represent different batches of the same formulation. These duplications were made in order to establish the ability of the supplier to reproduce individual formulations and the ability of laboratory personnel to repeat measurements made at different times.

B. Comparisons with Published Data

In order to establish the reliability of the technique described here, it is necessary to compare results obtained in this laboratory with published standard reference data. A convenient source of data for this purpose is the critically evaluated compilation of physical properties of hydrocarbons published by the American Petroleum Institute (Ref. 4).

n-Dodecane and n-hexadecane were selected as the reference materials for this comparison. The API tables give kinematic viscosity data for these fluids at 68°, 100°, 140°, 210°, 300°, and 400°F. Values at intermediate temperatures were calculated by fitting the reference data to the general formula

$$\log_e \frac{\nu_{100}}{\nu_t} = \frac{a(t-100) + b(t-100)^2}{c + t}$$

where ν_{100} is the kinematic viscosity at 100°F, ν_t is the viscosity at temperature t , and a , b , and c are parameters to be determined for each fluid. The following parameters were found to describe the viscosity-temperature relationships of n-dodecane and n-hexadecane:

TABLE I

DESCRIPTION OF FLUIDS STUDIED

<u>Identifying Code</u>	<u>Description</u>	<u>Viscosity at 100°F, cSt.</u>	<u>Maximum Temperature Studied, °F</u>
<u>n</u> -Dodecane	Matheson Coleman & Bell, Spectroquality	1.498	386.4
<u>n</u> -Hexadecane	Chemical Samples Company, 99.9%	3.055	493.9
0-64-1	MIL-L-27502 Type	25.47	494.4
0-64-2	MIL-L-23699 Type	27.51	610.1
0-64-20	Aromatic Ether, Experimental	24.24	700.2
0-65-12	MIL-L-7808F Type	14.99	495.6
0-67-0	Poly(phenyl ether), 5P4E	346.4	699.7
0-67-1	Formulated 5P4E Ether	356.6	594.8
0-67-4	MIL-L-27502 Type	29.24	494.0
0-67-7	MIL-L-007808F	17.37	481.2
0-67-9	MIL-L-7808G	15.10	471.8
0-67-10	Different Batch of 0-67-7	17.32	472.6
0-67-11	MIL-L-7808G	13.17	477.2
0-67-14	Different Batch of 0-64-20	24.54	640.0
0-67-20	MIL-L-7808G	13.44	472.6
0-68-1	MIL-L-7808 Type	13.28	469.7
0-68-7	MIL-L-7808G	13.65	475.0
0-68-12	MIL-L-7808 Type	13.44	474.3
0-68-13	MIL-L-7808 Type	14.63	476.3
0-68-17	MIL-L-7808G	12.96	484.9
0-69-5	Different Batch of 0-67-11	13.54	475.0
0-69-10	Different Batch of 0-67-11	13.40	473.0
0-69-17	MIL-L-27502 Type	27.81	490.0
0-69-19	MIL-L-27502 Type	29.24	495.6
0-70-2	MIL-L-7808 Type	13.99	493.2
0-70-6	MIL-L-27502 Type	28.90	493.6
0-70-7	MIL-L-7808 Type	12.75	494.8
0-70-10	MIL-L-27502 Type	32.67	640.0
MLO-62-1014	Silicone, Experimental	47.22	494.7
ATL-0111	Same as 0-67-10	17.39	494.7
ATL-0232	MIL-L-27502 Type	34.52	493.7
ATL-0233	MIL-L-27502 Type	27.22	493.8

	<u>a</u>	<u>b</u>	<u>c</u>
<u>n</u> -Dodecane	3.38316	4.334×10^{-4}	332.27
<u>n</u> -Hexadecane	3.33759	9.038×10^{-4}	216.59

Very pure samples of n-dodecane (Matheson Coleman and Bell Spectro-quality) and n-hexadecane (Chemical Samples Company, 99.9%) were obtained and their viscosities were determined over an extended temperature range. The results showed excellent agreement with calculated values from the API tables, as indicated in Table II. With one exception (n-hexadecane at 493.9°F, the highest temperature studied in this series), all of the data agree within 0.61%, and the average relative difference between the two sets is less than 0.35%. The experimental data are also shown graphically on an ASTM standard viscosity-temperature chart (Figure 9).

A number of synthetic lubricants included in this survey have also been investigated in another program at Southwest Research Institute; during the course of the SwRI program, viscosity data were determined at 100° and 210°F, and are reported in Refs. 5 and 6. A comparison of results obtained in this laboratory and at SwRI is given in Table III. In general, it can be seen that the agreement is excellent. Two interesting features appear in Table III. First, Table I reveals that lubricants ATL-0111 and 0-67-10 are identical, and are a different batch of 0-67-7. Both laboratories report very nearly the same results for all three samples (except for ATL-0111, which was not studied separately at SwRI). On the other hand, lubricants 0-67-11, 0-69-5, and 0-69-10 have the same nominal composition but are of different batches. In this case, both laboratories report subtle but noticeable differences among the three samples, indicating some slight batch variations. This observation suggests that a very careful viscosity determination is a useful quality control procedure.

C. Viscosity Data for Synthetic Lubricants

Complete viscosity data have been obtained for 30 synthetic lubricants over a wide temperature range, and the results are listed in Appendix A. In analyzing these data, it was found that they conform well to the general equation

$$\log_e \nu = A + B \log_e t + C/t ,$$

where ν is kinematic viscosity and t is the operating temperature in °F.

TABLE II

COMPARISON OF EXPERIMENTAL VISCOSITY DATA WITH PUBLISHED VALUES^{a/}

<u>Fluid</u>	<u>Temp. (°C)</u>	<u>Temp. (°F)</u>	<u>Kinematic Visc., cSt.</u>		<u>Difference (%)</u>
			<u>This Laboratory</u>	<u>API Tables</u>	
<u>n-Dodecane</u>	37.8	100.0	1.498	1.497	+0.07
	64.3	147.6	1.062	1.068	-0.56
	98.9	210.0	0.7447	0.7465	-0.24
	99.2	210.6	0.7480	0.7442	+0.51
	100.0	212.0	0.7371	0.7389	-0.24
	121.5	250.6	0.6169	0.6143	+0.42
	147.8	298.1	0.5042	0.5033	+0.18
	168.0	334.3	0.4412	0.4399	+0.30
	196.9	386.4	0.3695	0.3701	-0.16
<u>n-Hexadecane</u>	37.8	100.0	3.055	3.062	-0.23
	64.3	147.7	1.956	1.968	-0.61
	98.9	210.0	1.258	1.258	+0.00
	99.2	210.6	1.260	1.257	+0.24
	100.0	212.0	1.245	1.247	-0.16
	117.9	244.3	1.030	1.034	-0.39
	121.5	250.6	1.003	0.9993	+0.37
	146.9	296.5	0.7963	0.7968	-0.06
	167.8	334.1	0.6785	0.6773	+0.18
	197.8	388.1	0.5526	0.5515	+0.20
	230.0	446.0	0.4531	0.4552	-0.46
	256.6	493.9	0.3907	0.3951	-1.11

^{a/} Reference data taken from American Petroleum Institute tabulations
(Ref. 4).

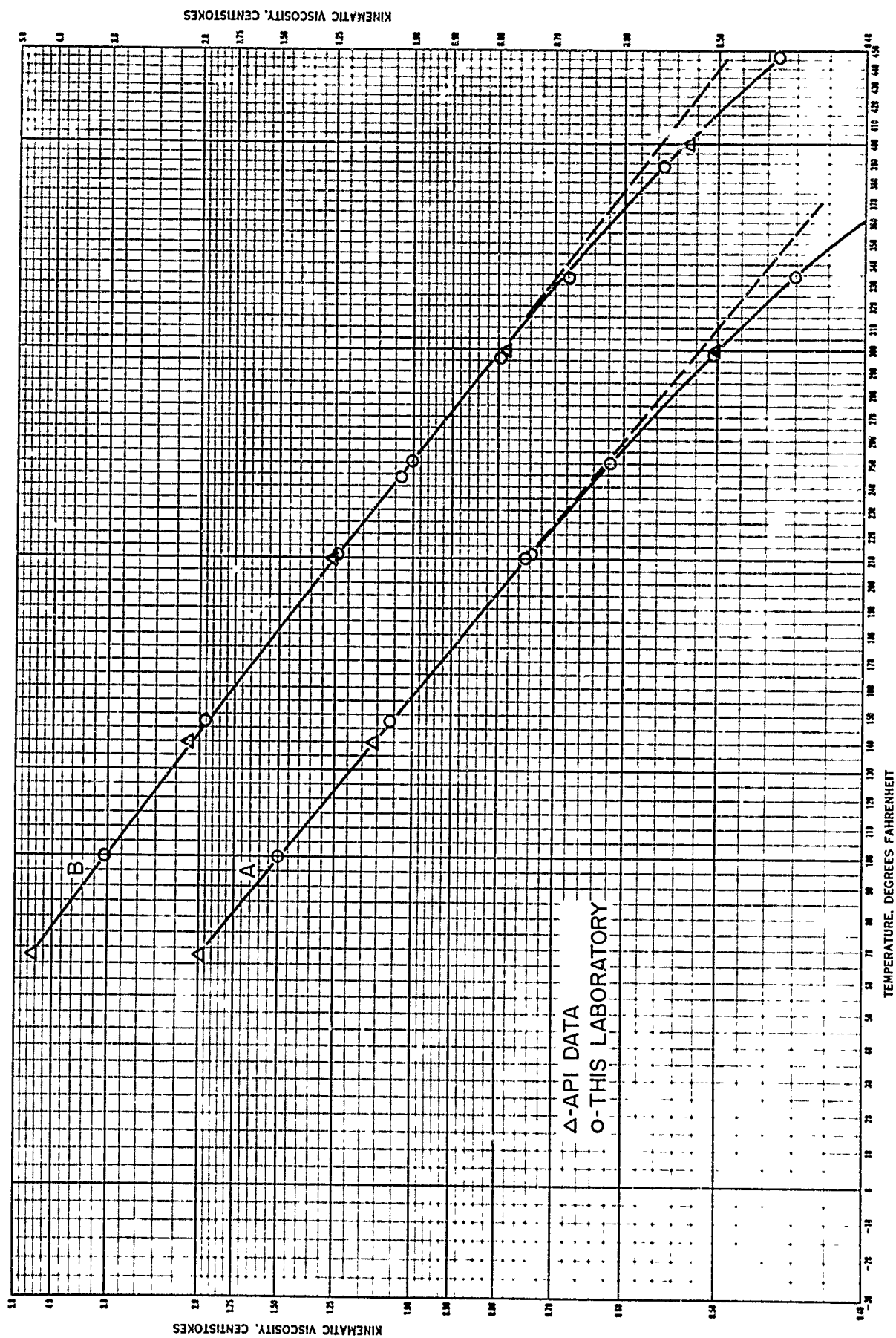


Figure 9 - Viscosity Temperature Plots for (A) n -Dodecane and (B) n -Hexadecane

TABLE III

COMPARISON OF LUBRICANT VISCOSITY DATA FROM TWO LABORATORIES

<u>Fluid</u>	<u>Kinematic Viscosity, cSt.</u>			
	<u>This Laboratory</u>		<u>SwRI^{a/}</u>	
	<u>100°F</u>	<u>210°F</u>	<u>100°F</u>	<u>210°F</u>
0-67-7	17.37	4.59	17.3	4.6
0-67-10	17.32	4.61	17.3	4.6
ATL-0111	17.39	4.62	--	--
0-67-11	13.17	3.23	13.3	3.2
0-69-5	13.54	3.24	13.6	3.2
0-69-10	13.40	3.24	13.5	3.2
0-64-1	25.47	5.06	26.0	5.1
0-64-2	27.51	5.07	27.5	5.1
0-64-20	24.24	4.10	24.2	4.1
0-67-1	356.6	13.05	357.6	13.0
0-67-4	29.24	5.43	29.2	5.4
0-67-9	15.10	3.75	14.8	3.7
0-67-20	13.44	3.23	13.5	3.2
0-68-1	13.28	3.20	13.3	3.2
0-68-7	13.65	3.39	13.7	3.4
0-68-12	13.44	3.25	13.5	3.2
0-68-13	14.63	3.57	14.6	3.6
0-68-17	12.96	3.46	13.0	3.4

^{a/} Reported by Southwest Research Institute (Refs. 5 and 6).

The parameters A , B , and C were found by least-squares analysis of the experimental data and are characteristic of each fluid. This empirical relationship will be discussed at length in a subsequent section. At present, however, it may be pointed out that the formula provides a very convenient method for tabulating viscosity data: the viscosity of each fluid can be accurately described over the entire temperature range of interest simply by tabulating the three empirical parameters.

A summary of all the viscosity data for 30 fluids is presented in this manner in Table IV. The three parameters A , B , and C were computed by least-squares treatment to give the best fit of the empirical formula to the available data. The parameters were then used to check the agreement of the formula with the experimental results obtained at each temperature. This agreement is indicated by the tabulated average error, which represents the average difference between the calculated and observed viscosity values over the entire temperature range covered.

The lowest temperature at which each lubricant was studied was 100°F, and the highest temperature is governed by the range of interest or by the thermal stability limits of the fluids under test. Each lubricant was tested to at least 470°F, and for two fluids (the aromatic ether formulations 0-64-20 and 0-67-0) it was possible to obtain data at 700°F. Apparently, some batch variations have an appreciable effect upon thermal stability, since we were unable to study lubricant 0-67-14, a different batch of 0-64-20, above 640°F because of thermal degradation. Once again, the highest temperature at which a repeatable viscosity measurement can be made is a potentially useful indicator of the thermal stability of a lubricant, and may prove valuable as a quality control procedure.

The viscosity data for the 30 lubricants are also shown graphically on ASTM standard viscosity-temperature charts (Appendix B, Figures 10-39). It will be noted that for n-dodecane and n-hexadecane (Figure 9), and all except two of the synthetic lubricants, these plots exhibit an appreciable deviation from linearity above about 300°F. Lubricant 0-70-10 yields a plot that does remain linear nearly to 400°F, and the plot for 0-67-0 is linear up to about 550°F. For the remaining fluids, the departure from linearity is quite apparent. This observation has been well documented for numerous fluids (Refs. 3, 7-10) and will be discussed in a later section. The ASTM plots do serve to demonstrate that serious errors can be introduced if one attempts to obtain high-temperature viscosity data by linear extrapolation from the low-temperature region. The magnitude of these errors can be seen from the data in Table V. Here, data are taken from the experimentally determined curves at 400°, 450°, and 500°F and compared with values found by extrapolation from the low temperature range. The extrapolated values are consistently high, and are typically in error by 5-7% at 400°F; the error is much greater (13.3%) for the silicone formulation, MLO-62-1014.

TABLE IV

CONDENSED SUMMARY OF EXPERIMENTAL VISCOSITY DATA^{a/}

<u>Lubricant Designation</u>	<u>Temp. Range, °F</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>Avg.^{b/} Error, %</u>
MIL-L-23699 Type					
0-64-2	100-610	11.534353	-1.907612	58.776659	1.10
MIL-L-27502 Type					
0-64-1	100-495	11.366448	-1.864857	47.332990	1.15
0-67-4	100-494	12.253875	-2.009232	38.905601	1.15
0-69-17	100-490	11.443835	-1.884784	58.007137	1.02
0-69-19	100-496	12.042183	-1.979777	46.261125	1.16
0-70-6	100-494	11.856084	-1.950287	50.419987	1.13
0-70-10	100-640	11.531669	-1.866362	64.721497	0.75
ATL-0232	100-494	12.166680	-1.987385	54.314271	1.32
ATL-0233	100-494	11.765916	-1.936922	47.281775	1.12
MIL-L-7808 Type					
0-65-12	100-496	10.820990	-1.787246	12.312006	0.52
0-67-7	100-481	11.314955	-1.823988	-6.199840	0.79
0-67-9	100-472	10.709504	-1.770271	15.762447	0.38
0-67-10	100-473	11.678310	-1.883163	-15.511216	0.44
0-67-11	100-477	10.469727	-1.757046	20.548692	0.59
0-67-20	100-473	10.447095	-1.754768	23.950040	0.96
0-68-1	100-470	10.862931	-1.821366	11.676358	0.92
0-68-7	100-475	10.272879	-1.717429	26.110381	0.77
0-68-12	100-474	10.457889	-1.756447	23.768388	0.85
0-68-13	100-476	10.759987	-1.788088	16.412220	0.62
0-68-17	100-485	10.663416	-1.765661	3.404563	0.49
0-69-5	100-475	10.293345	-1.729305	27.874613	0.61
0-69-10	100-473	10.344491	-1.738687	25.850662	0.36
0-70-2	100-493	10.926274	-1.799790	0.212420	0.39
0-70-7	100-495	10.612980	-1.756291	2.325958	0.35
ATL-0111	100-495	12.208953	-1.970166	-28.532332	0.93
Ether Type					
0-64-20	100-700	9.321819	-1.574463	106.475068	2.69
0-67-0	100-700	6.988602	-1.233027	455.059917	0.53
0-67-1	100-595	6.978324	-1.232910	459.190319	0.53
0-67-14	100-640	8.746667	-1.491882	134.143990	0.99
Silicone Type					
MLO-62-1014	100-495	16.199727	-2.400695	-129.898433	0.91

a/ Fitting by least squares analysis of experimental data to the form
 $\log_e v = A + B \log_e t + \frac{C}{t}$.

b/ Average difference between actual experimental data and values from
least-squares parametric equation.

TABLE V

COMPARISON OF EXPERIMENTAL AND EXTRAPOLATED VISCOSITY DATA^{a/}

Fluid	400°F			450°F			500°F		
	Exptl.	Estd.	Error (%)	Exptl.	Estd.	Error (%)	Exptl.	Estd.	Error (%)
n-Hexadecane	0.53	0.56	+5.7	0.45	0.49	+8.9	--	--	--
0-64-1	1.37	1.44	+5.1	1.09	1.18	+8.3	0.89	0.99	+11.2
0-65-12	1.15	1.21	+5.2	0.94	1.02	+8.5	0.78	0.86	+10.3
0-67-0	2.07	2.07	0.00	1.59	1.59	0.00	1.26	1.26	0.00
0-67-4	1.37	1.47	+7.3	1.08	1.19	+10.2	0.87	1.00	+14.9
0-67-9	1.16	1.21	+4.3	0.94	1.01	+7.4	0.76	0.86	+13.2
0-67-11	0.99	1.05	+6.1	0.81	0.87	+7.4	0.67	0.74	+10.4
0-68-1	0.99	1.08	+9.1	0.79	0.90	+13.9	0.64	0.77	+20.3
0-68-12	1.00	1.06	+5.7	0.81	0.88	+8.6	0.67	0.75	+11.9
0-68-17	1.10	1.16	+5.5	0.89	0.98	+10.1	0.73	0.83	+13.7
0-69-17	1.34	1.46	+9.0	1.06	1.19	+12.3	0.87	1.01	+16.1
0-69-19	1.35	1.44	+6.7	1.07	1.17	+9.3	0.87	0.98	+12.6
0-70-10	1.47	1.50	+2.0	1.16	1.22	+5.2	0.94	1.03	+9.6
MLO-62-1014	4.5	5.1	+13.3	3.5	4.2	+20.0	2.7	3.5	+29.6

^{a/} Data taken directly from ASTM viscosity-temperature charts: experimental values by interpolation between observed points; estimated values by extrapolation of linear portion from lower temperature region.

At higher temperatures, of course, the error is increased, and the extrapolated values at 500°F are typically 10-15% too high. Again, the error for MLO-62-1014 at 500°F is quite large (29.6%).

D. Variation of Viscosity with Temperature

The data in Appendix A have been fitted to a modification of a formula first proposed by Hovorka, Lankelma, and Stanford (Ref. 11). The formula used in treating the present set of viscosity results is a three-term parametric equation:

$$\log_e \nu = A + B \log_e t + C/t ,$$

where ν is the kinematic viscosity at $t^\circ\text{F}$, and A , B , and C are parameters characteristic of each fluid.

A least-squares technique was used to fit the experimental results. The summary in Table IV presents the best values for the parameters A , B , C for each fluid over the entire temperature range covered, along with the average difference between the actual experimental values and those computed using the least-squares parameters. These results indicate that it is possible, on the average, to calculate fluid viscosities from three experimentally determined parameters to well within 2% of the measured viscosities. In only one case (lubricant 0-64-20) was the fit poor enough to yield an expected error greater than 2%. The use of a parametric equation, such as that used here for reporting viscosity data, will be discussed at length in a subsequent section.

E. Analysis of Experimental Precision

The standard ASTM D445 test method for kinematic viscosity specifies that different results obtained by the same operator are acceptable if their spread is less than 0.35% of their mean value. Data reported by two different laboratories should not differ by more than 0.70% of their mean value. All of the determinations made in this laboratory are well within the 0.35% repeatability limit, and the results listed in Table III reveal that data from two independent laboratories agree consistently within the 0.70% reproducibility limit as well.

However, in order to evaluate the immediate and long-term reliability of the viscosity determinations reported here, it is necessary to perform a statistical analysis of the data. A parallel program was therefore carried

out in which several operators made viscosity measurements on three synthetic lubricants at random intervals over a period of 11 months. The most recent data for lubricant 0-64-2 were also compared with records on this fluid over a 5-year period.

The values in Table VI show a remarkable consistency for the viscosity of 0-64-2 at 100°F, which was monitored over a period of 5 years by at least seven different operators in three different laboratories. Considering only the nine listed values, the mean is 27.59 cSt. and the standard deviation is 0.16 cSt. (0.58% of the mean value).

TABLE VI

HISTORY OF VISCOSITY DATA FOR LUBRICANT 0-64-2

<u>Date Determined</u>	<u>Viscosity at 100°F (cSt.)</u>
August 1965 ^{a/}	27.45
November 1965	27.68
April 1966	27.77
July 1966	27.84
January 1967	27.57
January 1967	27.63
June 1967	27.36
May 1970 ^{b/}	27.5
May-November 1970 ^{c/}	<u>27.51</u>
Mean of nine reported values	27.59

^{a/} Data prior to 1968 are from unpublished results, University of Dayton Research Institute.

^{b/} Reported by Southwest Research Institute (Ref. 14).

^{c/} Current series: 97 independent determinations by four operators.

Listed in Table VII are the results of the statistical analysis of the viscosity data for three lubricants at 100° and 210°F. Five operators participated in this 11-month survey. A total of 97 measurements were made on 0-64-2 at 100°F; 89 measurements on 0-64-2 at 210°F; 111 measurements on 0-67-1 at 210°F; 95 measurements on 0-67-9 at 100°F; and 108 measurements on 0-67-9 at 210°F. These fluids and temperature conditions were selected so as to cover a wide viscosity range, with the determined values varying from 3.75 to 27.5 cSt., as indicated in Table VII. In each case, the standard deviation for the 100° measurements was less than 0.10% of the mean value; that for the 210° determinations was less than 0.20% of the mean value.

TABLE VII

STATISTICAL DATA FOR LUBRICANT VISCOSITY DETERMINATIONS

<u>Fluid</u>	<u>Temp. (°F)</u>	<u>Number of Operators</u>	<u>Number of Determinations</u>	<u>Mean Value (\bar{X})</u>	<u>Standard Deviation(σ)</u>	<u>$100\sigma/\bar{X}$^{a/}</u>	<u>95% Confidence Limits, cSt.^{b/}</u>
0-64-2	100	4	97	27.51	0.028	0.10	± 0.06
0-64-2	210	3	89	5.067	0.0053	0.10	± 0.011
0-67-1	210	3	111	13.11	0.026	0.20	± 0.05
0-67-9	100	3	95	15.10	0.012	0.08	± 0.03
0-67-9	210	3	108	3.751	0.0057	0.15	± 0.011

^{a/} Standard deviation expressed as percent of the mean value.

^{b/} Maximum variance, at the 95% confidence level, of a single determination from the mean value.

These results can be summarized as follows:

* At 100°F, we are 95% confident that a viscosity value reported by any of the five operators will be within 0.20% of the value that would be reported by the entire group.

* At 210°F, we are 95% confident that a viscosity value reported by any of the five operators will agree to within 0.40% of the value that would be reported by the entire group.

These studies were performed to confirm the reliability of the viscometry technique at 100° and 210°F. Although we do not have sufficient data to carry out an equivalent evaluation at higher temperatures, we feel that the technique and procedure described here are capable of yielding data of comparable validity over the entire range 100-700°F. This belief is based upon the following considerations: (1) temperature measurement and control are uniform throughout the entire range; (2) the viscosity measurement technique is the same over the entire range; (3) in practice, the repeatability of individual measurements is found to be comparable at all temperatures; and (4) there has been no indication that any change in the operation or performance of the apparatus occurs with changes in temperature.

It should be noted that these results do not make reference to the absolute accuracy of the data, since absolute values are not known for the materials tested. Although the various thermometer and viscometer calibrations are traceable to the National Bureau of Standards, it is not possible to assign true values to the materials for comparison. Where we have accepted the API reference data for n-dodecane and n-hexadecane as absolute, the agreement has been excellent, and this comparison shows that our efforts to eliminate or minimize sources of experimental error have been satisfactory.

V.

SIGNIFICANCE OF RESULTS

A. Evaluation of Test Conditions and Apparatus

It has been demonstrated that unusually close temperature control is necessary for precise viscosity measurements. The data in Table IV reveal that the variation of viscosity with temperature for the synthetic lubricants examined is typically on the order of 2.5% per degree at 100°F; 1.0% per degree at 200°F; and 0.5% per degree at 400°F. At the higher temperatures (above 300°F), less stringent controls can be employed, since a temperature fluctuation of 0.1°F results in a variation in viscosity of less than 0.1%. However, at lower temperatures, close temperature control becomes a critical factor. Since the apparatus described in Section III was designed with the capability of minimizing experimental errors due to temperature uncertainties, it is reasonable to apply it to yield the best control possible.

Experience with the high-temperature viscometer facility described in Section III has shown it to be eminently suitable to the requirements established for experimental precision. We are confident that errors due to temperature fluctuations are minimal, since our measurements show a typical temperature variation of less than $\pm 0.03^\circ\text{F}$ over the entire range 300-700°F.

The high-temperature capability of the apparatus has also met the 700°F objective set forth at the beginning of this work. Thus, the limiting factor in determining precise fluid viscosity data at high temperature is the thermal stability of the fluid being studied.

B. Precision of Experimental Results

The statistical analysis of the viscosity data presented in Tables VI and VII and discussed in Section IV-E indicates that the experimental results are well within the conventional $\pm 0.35\%$ repeatability limits. Good repeatability, as well as reproducibility, is supported by the results listed in Table III for measurements on replicate lubricant samples by different laboratories.

As stated previously, the viscosity data for synthetic lubricants cannot be evaluated in terms of their absolute accuracy, inasmuch as "true" values are not available for comparison. However, every aspect of the experimental procedure was tested in the measurement of the viscosities of

n-dodecane and n-hexadecane. Generally, excellent agreement was obtained when the results were compared with the best available reference data, as shown in Table II. If we accept the API reference data as absolute, then the agreement shown in Table II indicates that this laboratory is capable of producing data that are accurate to within $\pm 0.40\%$.

C. The Viscosity-Temperature Relationship

When physical property data are reported over a range of temperatures, it is customary to express the property-temperature relationship in a condensed analytical form. Density, for example, is commonly reported in the form

$$\rho = \alpha + \beta(t - t_0) + \gamma(t - t_0)^2 ,$$

where α is the density at some reference temperature t_0 , and β and γ are parameters characteristic of the material. If the data are very precise, or if they cover a wide temperature range, it may be necessary to add higher terms, such as $\delta(t - t_0)^3$, to describe the data adequately.

The density-temperature function is relatively simple, and one that the experimenter can deduce easily from his data. Other properties may vary with temperature in more complex ways, but usually the proper relationship is not too difficult to deduce. One may find, for example, that his property changes according to a Boltzmann-type function: $\log Q = k/T + C$, where Q is the measured property (vapor pressure, chemical reaction rate, etc.), T is the absolute temperature, and k is a proportionality constant giving additional information about the system (heat of vaporization, activation energy etc.).

Analytical descriptions of experimental data have great utility, since they enable one to calculate a desired property at any reasonable temperature without recourse to graphical interpolation or extrapolation. Their success depends, however, upon the ability of the experimenter to fit his data to an equation from which values can be computed with a precision approximating that of his experimental method. (Often, in fact, it happens that statistical analysis, such as a least-squares treatment of the data, leads to higher precision than the experimental technique because it tends to smooth out the effects of random errors in individual data points.)

Many workers have attempted, unsuccessfully, for many years to develop mathematical expressions that are generally applicable for describing the manner in which the viscosities of real fluids vary with temperature. In principle, one can use the methods of fluid mechanics, statistical mechanics, or even quantum mechanics to calculate any desired fluid property and to define its variation with temperature. These methods involve the solution of certain equations containing various intermolecular energy terms. A strictly rigorous approach takes into account all known intermolecular forces (dipole-dipole interactions, ionic forces, hydrogen bonding, London dispersion forces, π bonding, van der Waals interactions, etc.), and makes no prior assumptions about what the actual structure of the liquid might be (Refs. 12, 13). Unfortunately, under these conditions the equations cannot be solved for real systems except by approximate methods.

A semi-empirical approach has the advantage that certain simplifying approximations are made at the outset about the structure and nature of the liquid, so that a complete mathematical solution becomes possible, and approximations can then be made of the physical properties of interest. This technique has been widely developed by Eyring in his significant structure theory of liquids (Refs. 14-16). Eyring has been able to make some remarkably accurate predictions of certain thermodynamic properties (heat capacity, molar volume, entropy of fusion, critical temperature, vapor pressure, etc.). However, this success has been limited to relatively simple systems, such as condensed noble gases, halogens, *o*- and *p*-hydrogen, and methane. Because of the simplifying assumptions, the theory lacks the refinement needed for dealing accurately with the viscosities of more complex materials, and particularly complex mixtures.

Thus, the rigorous mathematical approach has the intellectual appeal of mathematical elegance, but is not amenable to unique solutions describing the nature of real fluids. Conversely, the semi-empirical model method is conceptually simple and straightforward, but the built-in assumptions and approximations lead to a sacrifice in both the accuracy and precision needed for predicting viscosity values.

For further details on the theoretical and semi-empirical treatments of fluid viscosity, the reader is particularly referred to the excellent and highly entertaining review by Brush (Ref. 13). In addition to a candid summary of the advantages and disadvantages of the two approaches, Brush presents a discussion of the totally empirical method, in which the mathematical analysis of viscosity data need have no basis in theory at all. The purpose here is simply to fit observed data to workable formulas. Numerous functions are tabulated, which various authors have proposed for fitting their viscosity-temperature data. Similar series of such formulas have been tabulated by Partington (Ref. 17) and by Doolittle (Ref. 18). Although Brush warns against attaching any theoretical significance to these

"monstrous" functions, still they do have great practical usefulness if they fit the experimental data accurately enough and are convenient to handle.

Many of the formulas cited by Brush, Partington, and Doolittle involve logarithmic and/or power-series expansions in temperature, and many are merely variations on Andrade's (Ref. 19) strictly Boltzmann-type viscosity-temperature relationship. It is true that, over limited temperature ranges, relationships such as Andrade's ($\log v = K/T + C$) may be valid. However, very few of the proposed relationships appear to have universal applicability, i.e., the ability to fit the available data with good precision over substantial regions of the liquid ranges of different classes of fluids.

Noteworthy by its absence from the literature tabulations is the formula mentioned previously for fitting the data for n-dodecane and n-hexadecane;

$$\log_e \frac{v_{100}}{v_t} = \frac{a(t - 100) + b(t - 100)^2}{c + t}$$

where v_{100} is the (kinematic) viscosity at 100°F, v_t is the viscosity at temperature t (°F), and a , b , and c are characteristic parameters. This general form fits the available data for paraffins very well, but its precision decreases somewhat as the temperature range is extended. It has been used by Cannon Instrument Company for defining the viscosity behavior of the ASTM calibrating fluids over the temperature range 68 - 150°F with a maximum error 0.16% (Ref. 2). Surprisingly, this same formula is applied by the National Bureau of Standards to the standard reference data for water--a most dissimilar fluid indeed--with a maximum error of 0.1% over the range 20-75°C, and a maximum error of 0.16% up to 150°C (Refs. 20-22).

We have found that a formula first proposed by Hovorka, Lankelma, and Stanford (Ref. 11) does adequately describe the viscosity-temperature relationship of the synthetic lubricants studied here. Entirely empirical, it follows closely the observed variation of viscosity with temperature over the entire temperature range studied. The formula is a three-term parametric equation,

$$\log_e v = A + B \log_e t + C/t ,$$

where in our analysis v is kinematic viscosity, t is the test temperature in °F, and A , B , and C are constants to be evaluated for each fluid.

The complete set of experimental data given in Appendix A was processed by a least-squares analysis to give the best values of A, B, and C listed in Table IV. These values for each fluid were then used to calculate corresponding viscosity values at each temperature studied. This procedure provides an estimate of the agreement of the formula with the experimental data; the average difference for each set of data, also shown in Table IV, is consistent over the entire temperature range in all cases, indicating that the three-parameter equation faithfully describes the shape of the viscosity-temperature curve.

The results given in Table IV reveal that the curve-fitting process is more successful for certain classes of fluids than for others. For example, use of the known parameters for a MIL-L-7808 fluid can be expected to yield a calculated viscosity value that is within 1% of the experimentally determined value at any temperature between 100° and 500°F. The agreement is only slightly poorer for the MIL-L-23699, MIL-L-27502, ether, and silicone formulations: only with lubricant 0-64-20 is the average difference between the calculated and observed values greater than 2%.

It is felt that this precision is adequate for most practical applications, and certainly the format for reporting viscosity data by means of three characteristic parameters offers great convenience. For example, one can readily compute a desired viscosity at any temperature within the reported range by performing the algebraic operations required by the modified Hovorka-Lankelma-Stanford formula. This task is particularly easy if one has access to a desk calculator having single-stroke $\log_e x$ and e^x functions. The calculated values are, furthermore, more precise than those that might be obtained by extrapolation or interpolation from tabular or graphical presentations of the data.

An added advantage of this viscosity-temperature formula, which became apparent upon examination of the standard ASTM viscosity-temperature plots for the 30 lubricants studied, is that it predicts deviations of these plots from linearity below 100°F as well as above 300°F. Examination of the ASTM plots (Figures 10-39) reveals that in nearly every case the behavior is far from linear. If one estimates a lubricant viscosity at 500°F, for example, by linear extrapolation from the data points at 100°F and 210°F on an ASTM chart, the estimate is likely to be at least 10% too high (see Table V), whereas calculated values using the parametric equation are likely to be well within 2% of the experimentally determined values. Similarly, close examination shows that viscosity data plotted on the ASTM chart tend to deviate upward at temperatures below 100°F. This trend is also predicted by the parametric equation.

A single, and valid, objection to the use of a parametric equation of the form used here is that it does not yield a defined value at 0°F, i.e., a viscosity value cannot be calculated at 0°F because the mathematical functions are undefined at that temperature. Furthermore, the formula predicts that the viscosity of the fluid should pass through a maximum at $t = C/B$, an effect that is not observed with real fluids. However, for most of the fluids studied here the ratio C/B is negative, and the function does not have algebraically real values for negative values of t . In any event, for the four cases where C/B is positive, the quotient is small (less than 15°), and the falsely predicted viscosity maxima are far enough removed from the temperature region of interest that the agreement between the calculated data and the values obtained in practice is not affected.

In summary, we find numerous advantages in terms of convenience and precision in the use of the three-parameter viscosity-temperature function for describing the observed variation of lubricant viscosity with temperatures above 100°F. There are valid objections to its use on purely mathematical grounds, but it is not intended to be used under conditions where the stated mathematical and physical difficulties would occur.

VI.

CONCLUSIONS AND RECOMMENDATIONS

The procedure described in this report has been shown to be successful for determining fluid viscosity data with excellent precision within the entire temperature range 100°-700°F. Temperature control and measurement capabilities are uniform throughout this entire temperature range, and meet accepted standards for viscosity measurement. From the results listed in Table VII, we calculate that the repeatability of our technique is on the order of $\pm 0.30\%$.

Conventional methods for reporting and analyzing viscosity data below 300°F are inadequate to predict viscosity values accurately at higher temperatures. It has been shown that linear extrapolation of data plotted on standard viscosity-temperature charts may introduce errors as great as 12-15% for two classes of synthetic lubricants at 500°F. A formula has been examined, however, and has been found successful in expressing the viscosity-temperature relationship faithfully at temperatures above 100°F. By summarizing a complete set of viscosity data for a fluid lubricant by means of three experimentally determined parameters, it is possible to compute viscosity values that are well within 2% of the experimental values throughout the entire temperature range of interest.

This capability for reporting and computing reliable viscosity values at high temperatures requires that the characteristic parameters in the viscosity-temperature formula be determined by a series of careful experimental measurements over a wide temperature range. The high-temperature viscometry facility described in this report provides a means for obtaining the necessary data.

Knowledge of lubricant viscosity in a high-temperature environment is essential for a viable analysis of the effect of lubricant behavior upon the performance of mechanical parts and assemblies. It is therefore recommended that this direct experimental determination of fluid lubricant viscosity above 300°F be adopted as an integral part of a complete lubricant evaluation program.

The experimental facility developed for this work admittedly incorporates stringent controls and requirements that were considered necessary for proving the feasibility of, and indeed the need for, the experimental technique, but which may yield more highly refined and precise data than are required in engineering practice. It is therefore further recommended that a review of the viscometry facility be undertaken in an effort to eliminate unnecessary refinements. For example, in practice it is found

that temperature control and measurement to within $\pm 0.1^\circ$ may be adequate for viscosity determinations above about 250°F. This precision is within the capability of some thermistor and thermocouple systems, which are far less costly than the high-precision platinum resistance thermometric technique used here. By providing adequate precision under more economically favorable terms, it may be possible to bring the high-temperature lubricant viscometry within the scope of any testing laboratory.

APPENDIX A

VISCOSITIES OF SYNTHETIC LUBRICANTS

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Fluid	Temperature		Viscosity (cSt.)	Fluid	Temperature		Viscosity (cSt.)	Fluid	Temperature		Viscosity (cSt.)
	T, °C	T, °F			T, °C	T, °F			T, °C	T, °F	
0-64-1	37.8	100.0	25.47	0-65-12 (Conc.)	197.7	387.8	1.223	0-67-7 (Conc.)	120.0	248.0	3.430
	60.3	140.5	12.33		230.1	446.3	0.949		120.7	249.3	3.360
	98.9	210.0	5.057		257.6	495.6	0.783		134.3	273.8	2.876
	127.6	261.7	3.164	0-67-0	37.8	100.0	346.4	0-67-9	141.4	286.5	2.640
	143.3	289.9	2.580		60.3	140.5	63.55		157.5	315.4	2.262
	176.8	350.3	1.762		81.9	179.4	23.02		169.3	336.7	1.971
	196.6	358.5	1.454		98.9	210.0	12.93		173.0	343.3	1.907
	229.1	444.3	1.112		115.5	239.9	8.430		180.3	356.5	1.776
	256.9	494.4	0.911		120.0	248.1	7.554		187.8	370.0	1.691
					120.9	249.7	7.415		210.0	410.0	1.408
					130.1	266.2	6.093		218.2	424.7	1.308
0-64-2	37.8	100.0	27.51	0-67-1	37.8	100.0	356.6	0-67-10	37.8	100.0	17.32
	60.3	140.5	12.83		60.3	140.5	64.63		98.9	210.0	4.611
	81.9	179.4	7.299		81.9	179.4	23.15		134.6	274.4	2.852
	98.9	210.0	5.066		98.9	210.0	13.05		153.6	308.5	2.320
	114.9	238.7	3.792		115.5	239.9	8.450		165.6	330.0	2.039
	115.6	240.1	3.774		123.3	253.9	7.144		227.0	440.1	1.204
	125.8	258.4	3.170		130.1	266.2	6.172		244.8	472.6	1.041
	130.1	266.2	2.994		137.5	279.5	5.370	0-67-11	37.8	100.0	13.17
	146.6	296.0	2.368		160.4	320.7	3.656		66.0	150.8	6.103
	157.0	314.7	2.074		168.7	335.7	3.245		98.9	210.0	3.232
	160.2	320.4	1.998		173.4	344.2	3.040		135.0	275.0	1.941
	200.0	392.0	1.339		198.6	389.4	2.237		163.4	326.3	1.433
	227.4	441.4	1.056		213.5	416.3	1.914	0-67-14	211.8	413.2	0.937
	241.8	467.3	0.935		239.5	463.0	1.499		247.3	477.2	0.728
	251.9	485.5	0.871		287.5	549.6	1.028		37.8	100.0	24.54
	257.0	494.6	0.846		304.5	580.0	0.921		65.6	150.2	8.926
	287.8	550.0	0.674		312.7	594.8	0.874		81.9	179.4	5.863
	304.5	580.0	0.608	0-67-4	37.8	100.0	29.24		98.9	210.0	4.118
	321.1	610.1	0.549		60.0	140.0	13.86		115.8	240.4	3.101
0-64-20	37.8	100.0	24.24		80.0	176.0	8.145		120.0	248.1	2.880
	65.6	150.1	8.843		98.9	210.0	5.428		130.1	266.2	2.498
	81.9	179.4	5.833		120.0	248.0	3.756		147.6	297.8	2.001
	98.9	210.0	4.099		147.7	297.8	2.526		163.6	326.5	1.656
	115.5	239.9	3.080		176.9	350.5	1.789		166.5	331.8	1.616
	120.0	248.0	2.859		196.7	386.1	1.461		176.6	349.8	1.462
	130.1	266.2	2.476		229.7	445.5	1.098		201.2	394.1	1.171
	147.6	297.6	1.990		256.7	494.0	0.891		229.1	444.3	0.953
	165.6	330.0	1.612	0-67-7	37.8	100.0	17.37		232.2	450.0	0.936
	175.5	349.6	1.457		98.9	210.0	4.585		246.1	475.0	0.851
	177.0	350.6	1.454		114.3	237.8	3.692		256.5	493.7	0.797
	205.0	401.0	1.135						287.7	549.9	0.650
	210.0	410.0	1.083								
	229.6	445.3	0.939								
	232.1	449.8	0.930								
	256.9	494.0	0.784								
	287.6	549.8	0.647								
	304.4	580.0	0.593								
	320.7	609.3	0.564								
	337.9	640.2	0.523								
	354.1	669.4	0.490								
	371.2	700.2	0.464								
0-65-12	37.8	100.0	14.99								
	60.2	140.4	8.061								
	98.9	210.0	3.728								
	120.0	248.1	2.752								
	166.4	331.6	1.618								

Fluid	Temperature		Viscosity (cSt.)	Fluid	Temperature		Viscosity (cSt.)	Fluid	Temperature		Viscosity (cSt.)
	T, °C	T, °F			T, °C	T, °F			T, °C	T, °F	
0-67-14 (Conc.)	304.6	580.3	0.594	0-68-17 (Conc.)	98.9	210.0	3.462	0-69-19 (Conc.)	230.1	446.2	1.085
	320.1	609.9	0.552		116.2	241.2	2.698		257.5	495.6	0.887
	337.8	640.0	0.515		125.3	257.6	2.385				
0-67-20	37.8	100.0	13.44		130.9	267.6	2.232	0-70-2	37.8	100.0	13.99
	66.0	150.8	6.197		137.1	278.0	2.074		65.6	150.0	6.773
	98.9	210.0	3.230		142.1	287.7	1.966		82.2	180.0	4.888
	121.0	249.8	2.377		147.4	297.4	1.851		98.9	210.0	3.669
	134.6	274.2	1.948		149.5	301.1	1.811		115.6	240.0	2.896
	160.5	320.9	1.471		150.8	303.5	1.789		132.2	270.0	2.327
	175.1	347.1	1.280		155.3	315.1	1.673		148.9	300.0	1.928
	219.7	427.5	0.885		161.7	323.0	1.613		162.8	325.0	1.677
	244.8	472.6	0.740		166.3	331.3	1.535		176.7	350.0	1.466
0-68-1	37.8	100.0	13.28		168.9	336.0	1.490		193.3	380.0	1.271
	60.0	140.0	7.069		188.5	371.3	1.260		210.0	410.0	1.111
	65.0	149.0	6.261		207.8	406.1	1.077		276.7	440.1	0.979
	98.9	210.0	3.202		217.0	422.6	0.999		243.3	470.0	0.864
	135.0	275.0	1.984		232.3	450.2	0.898		256.2	493.2	0.785
	156.3	313.4	1.523		251.6	484.9	0.772				
	226.5	439.8	0.830								
	243.2	469.7	0.725	0-69-5	37.8	100.0	13.54	0-70-6	37.8	100.0	28.90
0-68-7	37.8	100.0	13.65		80.0	176.0	4.588		65.6	150.0	11.55
	60.3	140.5	7.300		98.9	210.0	3.243		82.2	180.0	7.586
	99.1	210.3	3.387		120.0	248.0	2.378		98.9	210.0	5.321
	128.3	262.9	2.221		168.2	334.8	1.367		115.6	240.0	3.943
	129.0	264.2	2.199		227.2	441.0	0.847		132.2	270.0	3.040
	134.6	274.3	2.059	0-69-10	246.1	475.0	0.737		148.9	300.0	2.423
	136.8	278.1	2.006		37.8	100.0	13.40		162.8	325.0	2.047
	164.0	327.2	1.494		98.9	210.0	3.240		176.7	350.1	1.760
	167.6	333.6	1.442		135.0	275.0	1.950		193.3	380.0	1.489
	167.9	334.2	1.439		160.0	320.3	1.475		210.0	410.0	1.277
0-68-12	185.9	366.7	1.230		226.9	440.4	0.839		226.7	440.0	1.110
	218.0	424.4	0.950		245.0	473.0	0.733		243.3	470.0	0.974
	246.1	475.0	0.781	0-69-17	37.8	100.0	27.81		256.4	493.6	0.886
					60.0	140.0	13.17	0-70-7	37.8	100.0	12.75
					98.9	210.0	5.246		65.6	150.0	6.266
					111.2	232.1	4.188		82.2	180.0	4.519
					120.0	248.0	3.616		98.9	210.0	3.428
					134.0	273.2	2.920		115.6	240.0	2.704
0-68-13	37.8	100.0	13.44		151.4	304.5	2.348		132.2	270.0	2.188
	60.0	140.1	7.132		155.7	312.2	2.219		148.9	300.0	1.822
	98.9	210.0	3.253		159.3	318.8	2.122		162.8	325.0	1.583
	135.0	275.0	1.958		161.2	322.1	2.064		176.7	350.0	1.393
	158.2	316.8	1.501		165.8	330.4	1.965		193.3	380.0	1.208
	227.0	440.5	0.833		186.9	368.4	1.588		210.0	410.0	1.060
	245.7	474.3	0.738		206.5	403.7	1.320		226.7	440.0	0.936
					223.6	434.5	1.136		243.3	470.0	0.829
					241.7	467.1	0.989		257.1	494.8	0.752
0-68-17	37.8	100.0	12.96		243.1	469.6	0.984	0-70-10	37.8	100.0	32.67
	66.0	150.8	6.268		254.4	490.0	0.908		98.9	210.0	5.936
	77.0	170.5	5.029	0-69-19	37.8	100.0	29.24		121.0	249.8	3.986
					60.0	140.0	13.67		132.2	270.0	3.361
					98.9	210.0	5.374		148.9	300.0	2.567
					120.0	248.0	3.654		162.7	324.9	2.247
					147.6	297.6	2.488		176.6	350.0	1.916
					172.1	341.8	1.859		193.3	380.0	1.635
					197.4	387.4	1.440		210.0	410.0	1.395
									226.4	439.5	1.217

Fluid	Temperature		Viscosity (cSt.)	Fluid	Temperature		Viscosity (cSt.)	Fluid	Temperature		Viscosity (cSt.)
	T, °C	T, °F			T, °C	T, °F			T, °C	T, °F	
0-70-10 (Cont.)	243.3	470.0	1.071	MLO-62-1014 (Conc.)	253.0	451.4	3.360	ATL-0232 (Conc.)	176.7	350.0	1.954
	256.5	493.7	0.968		244.9	472.8	3.125		193.3	380.0	1.639
	287.8	550.0	0.773		257.1	494.7	2.808		210.0	410.0	1.405
	304.4	580.0	0.699	ATL-0111	37.8	100.0	17.39		226.5	439.6	1.223
	321.1	610.0	0.633		60.0	140.0	9.600	ATL-0233	243.3	470.0	1.072
	337.8	640.0	0.580		98.9	210.0	4.621		256.5	493.7	0.968
MLO-62-1014	37.8	100.0	47.22	ATL-0232	120.0	248.0	3.419		37.8	100.0	27.22
	65.6	150.1	26.87		147.6	297.6	2.448		65.6	150.0	11.06
	81.9	179.4	20.18		177.2	351.0	1.822		82.2	180.0	7.268
	98.9	210.0	15.33		230.2	446.4	1.143		98.9	210.0	5.161
	115.5	239.9	12.29		257.1	494.7	0.913	ATL-0233	115.6	240.0	3.842
	129.4	265.0	10.17	ATL-0232	37.8	100.0	34.52		132.2	270.0	2.954
	130.1	266.2	10.09		65.6	150.0	13.43		148.9	300.0	2.363
	150.0	302.0	7.95		82.2	180.0	8.724		162.8	325.0	2.000
	163.8	326.9	6.824		98.9	210.0	6.101		176.7	350.0	1.723
	174.1	345.3	6.056		115.6	240.0	4.469		193.3	380.0	1.461
	190.2	374.3	5.145		132.2	270.0	3.409		210.0	410.0	1.256
	195.3	383.6	4.866		148.9	300.0	2.703		227.0	440.6	1.088
	213.4	416.1	4.099		160.0	320.1	2.353		243.3	470.0	0.960
	217.4	423.4	3.973						250.6	493.8	0.875
	230.4	446.7	3.533								

APPENDIX B

ASTM VISCOSITY-TEMPERATURE PLOTS FOR
SYNTHETIC TURBINE ENGINE LUBRICANTS

(Figures 10 through 39)

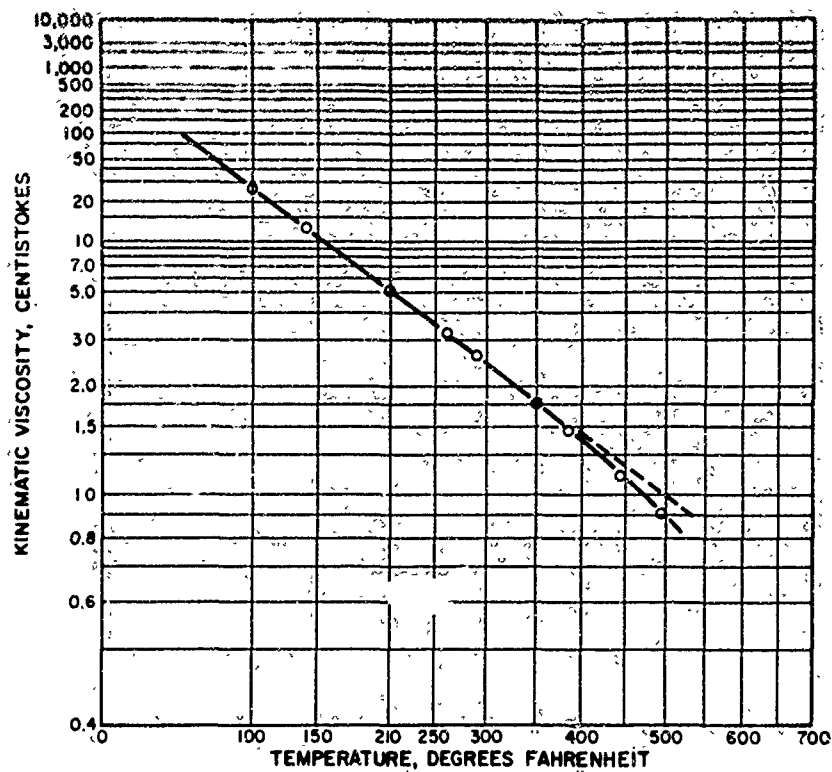


Figure 10 - Viscosity-Temperature Plot for 0-64-1

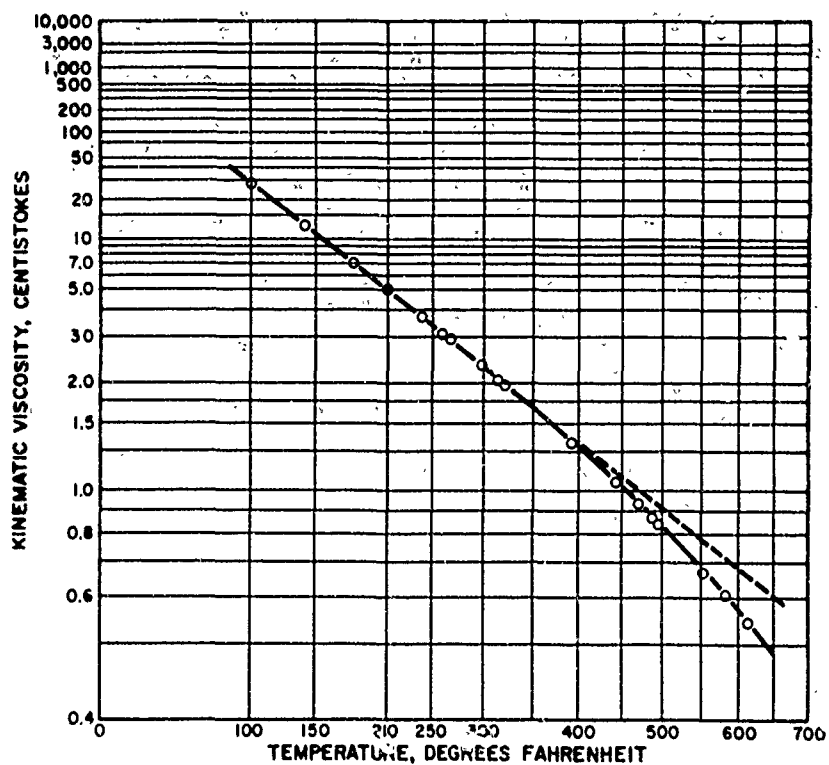


Figure 11 - Viscosity-Temperature Plot for 0-64-2

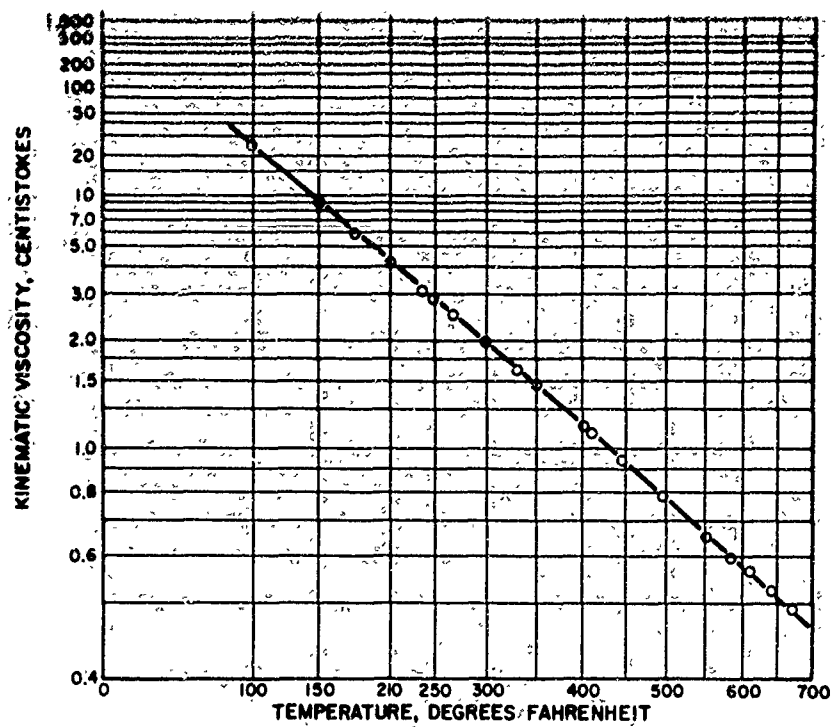


Figure 12 - Viscosity-Temperature Plot for 0-64-20.

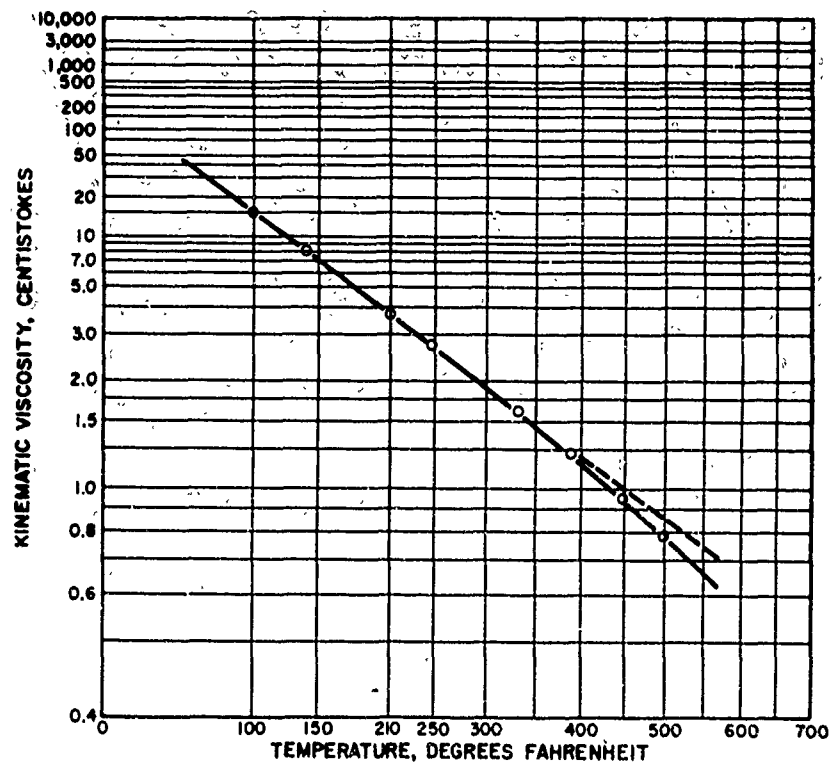


Figure 13 - Viscosity-Temperature Plot for 0-65-12

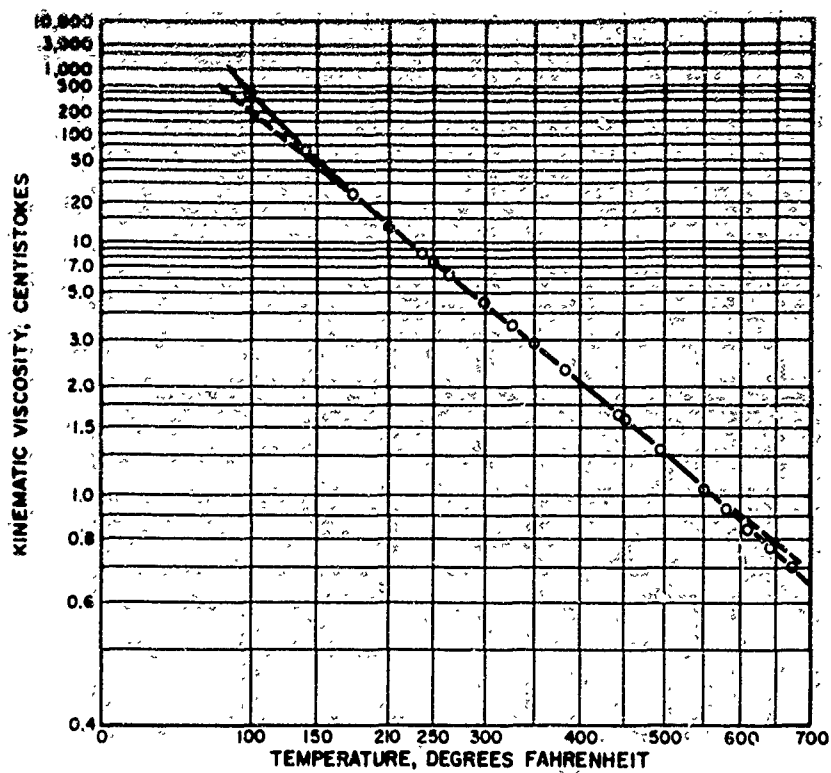


Figure 14 - Viscosity-Temperature Plot for 0-67-0

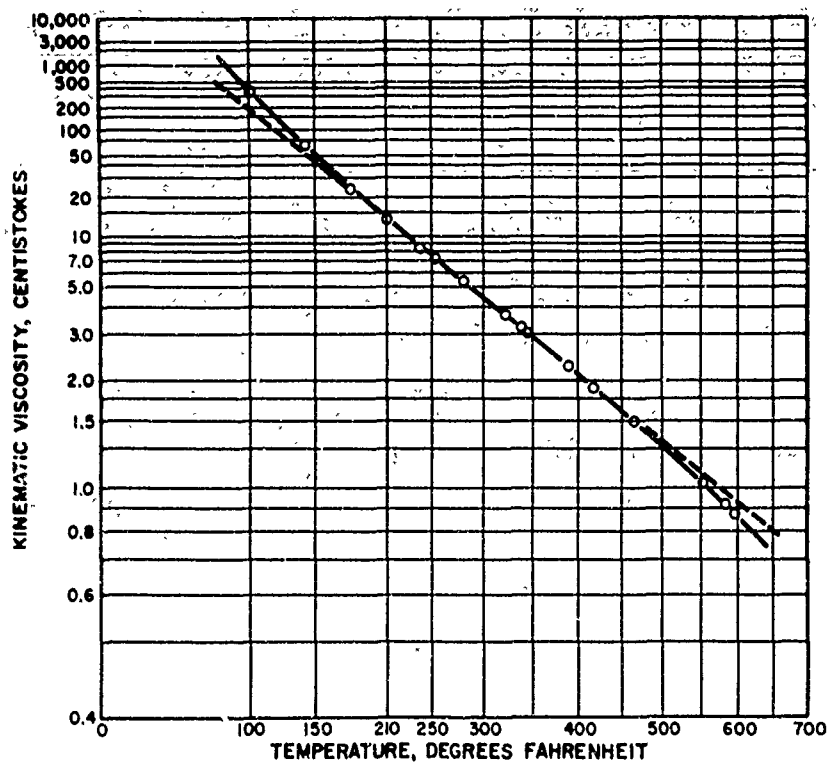


Figure 15 - Viscosity-Temperature Plot for 0-67-1

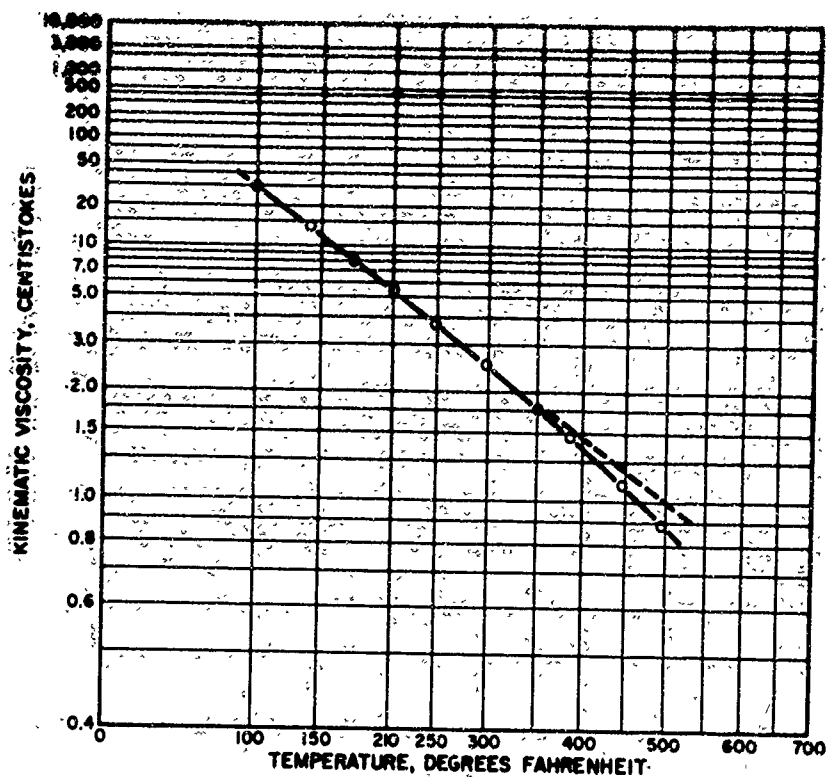


Figure 16 - Viscosity-Temperature Plot for 0-67-4

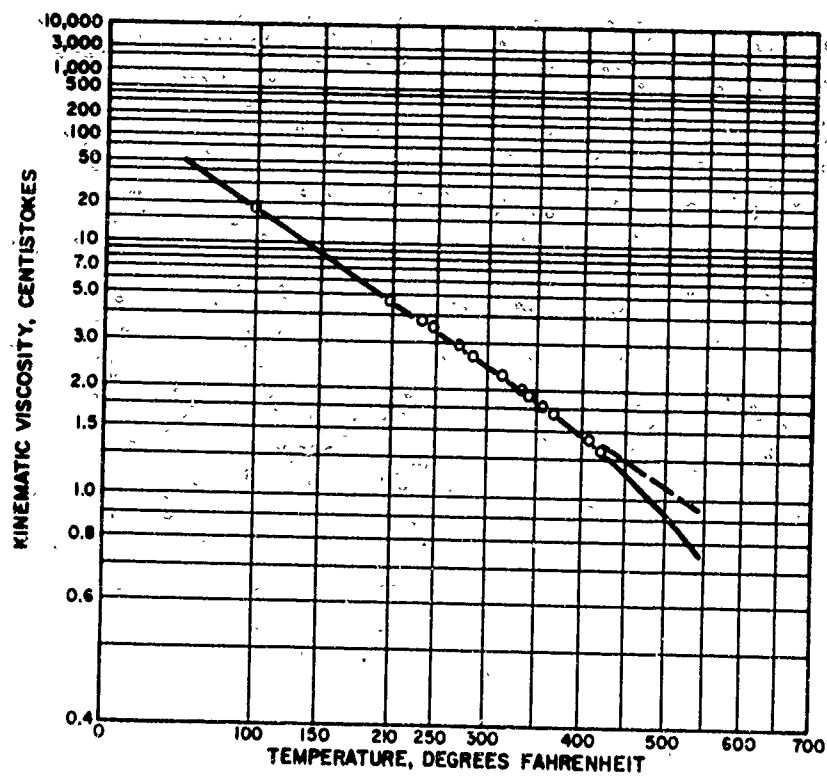


Figure 17 - Viscosity-Temperature Plot for 0-67-7

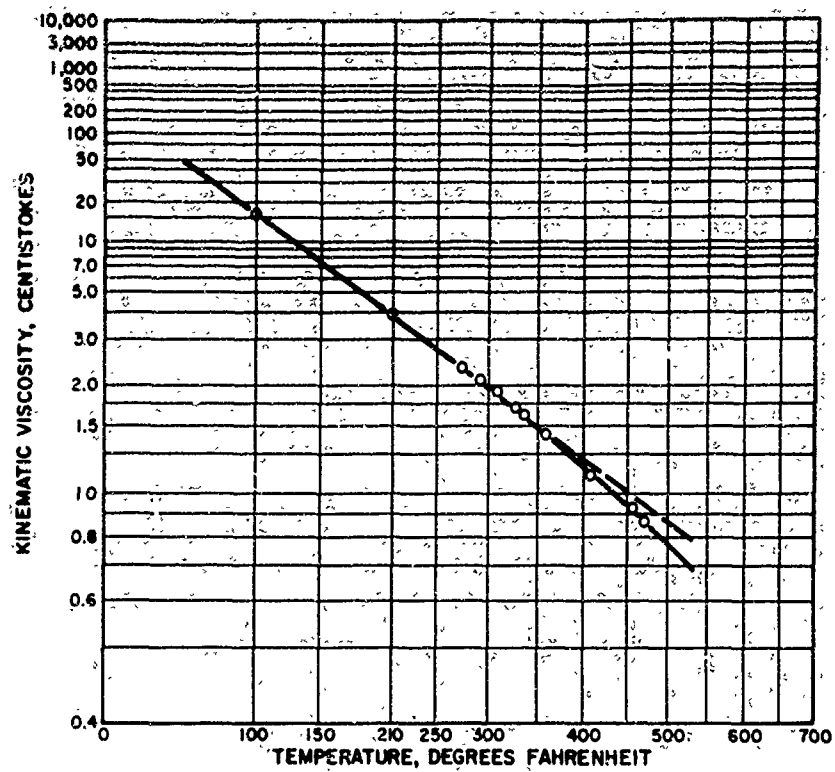


Figure 18 - Viscosity-Temperature Plot for 0-67-9

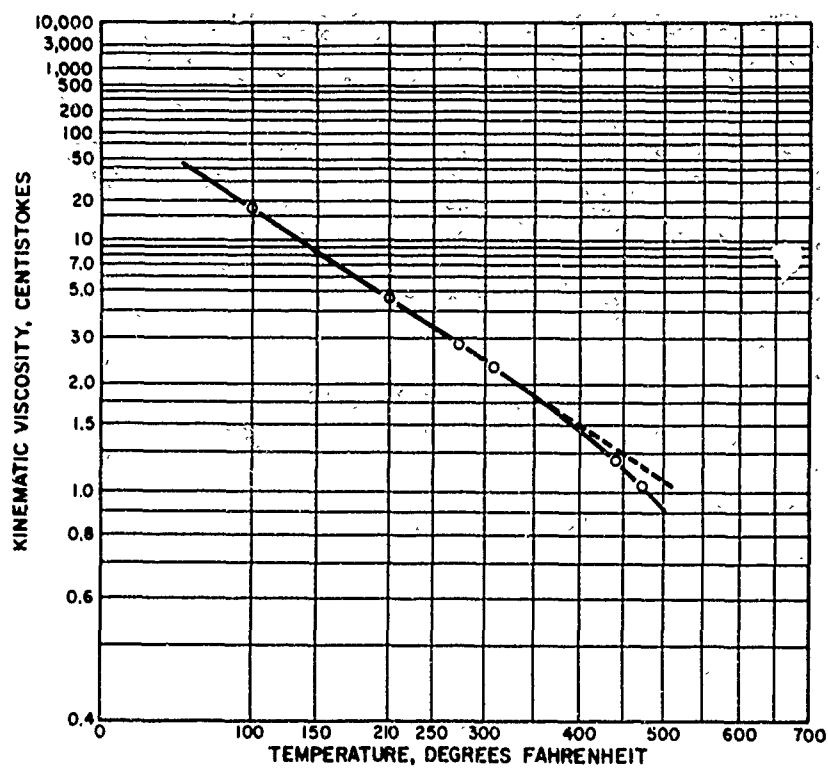


Figure 19 - Viscosity-Temperature Plot for 0-67-10

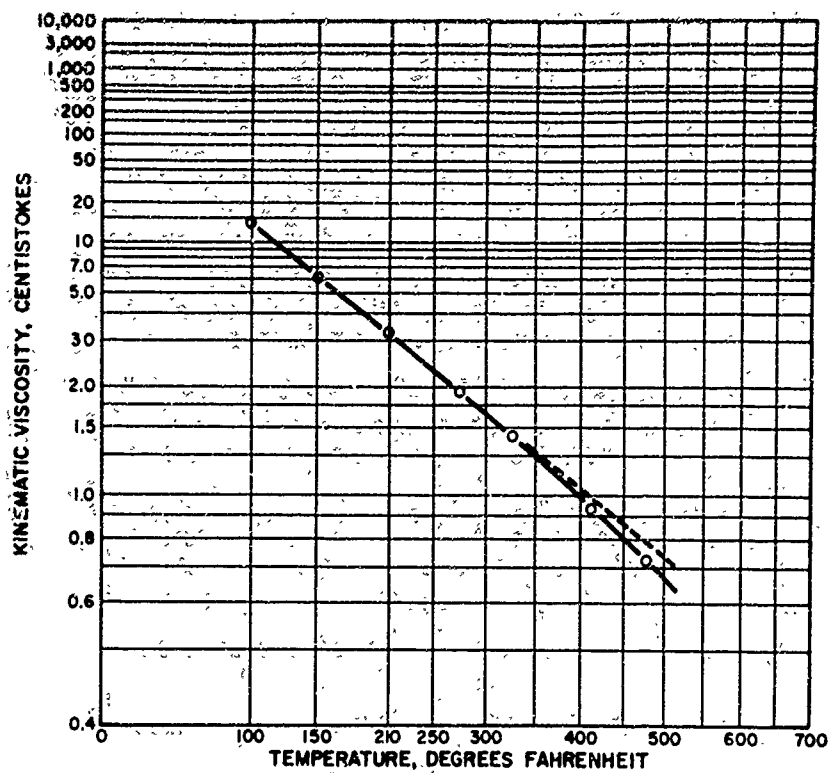


Figure 20 - Viscosity-Temperature Plot for 0-67-11

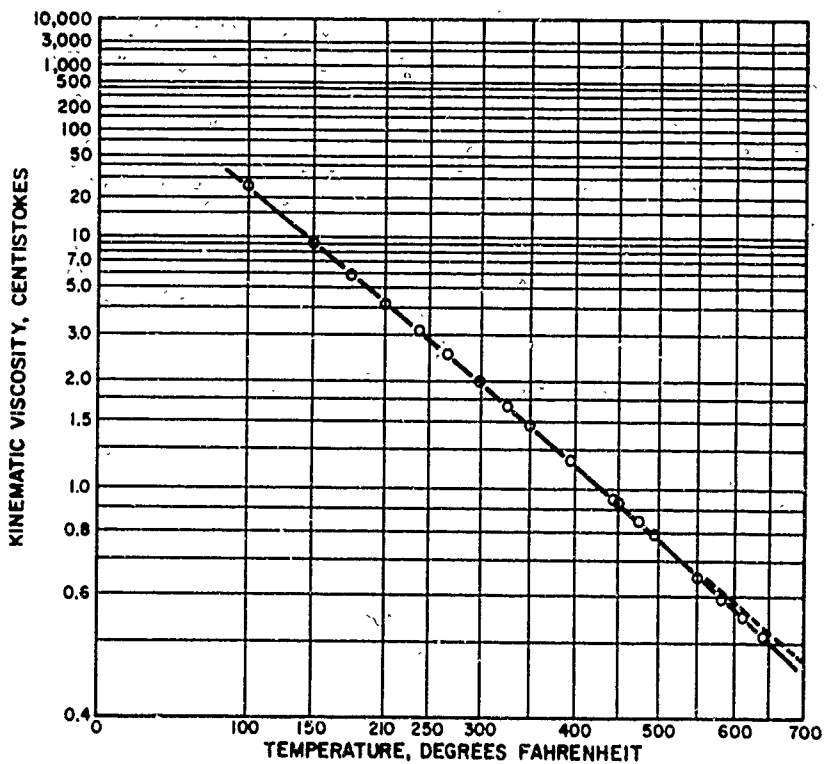


Figure 21 - Viscosity-Temperature Plot for 0-67-14

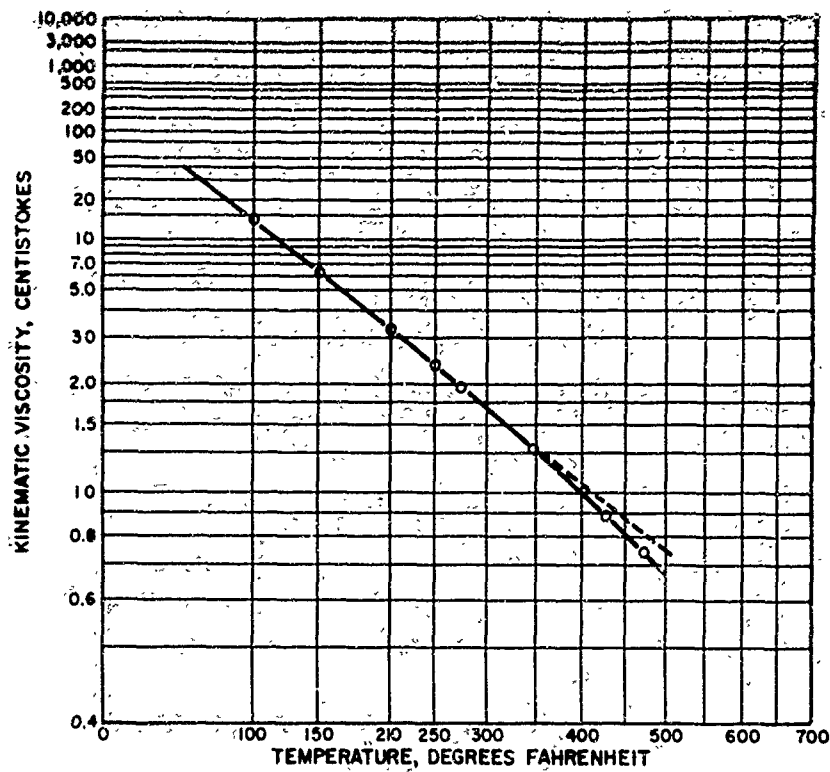


Figure 22 - Viscosity-Temperature Plot for 0-67-20

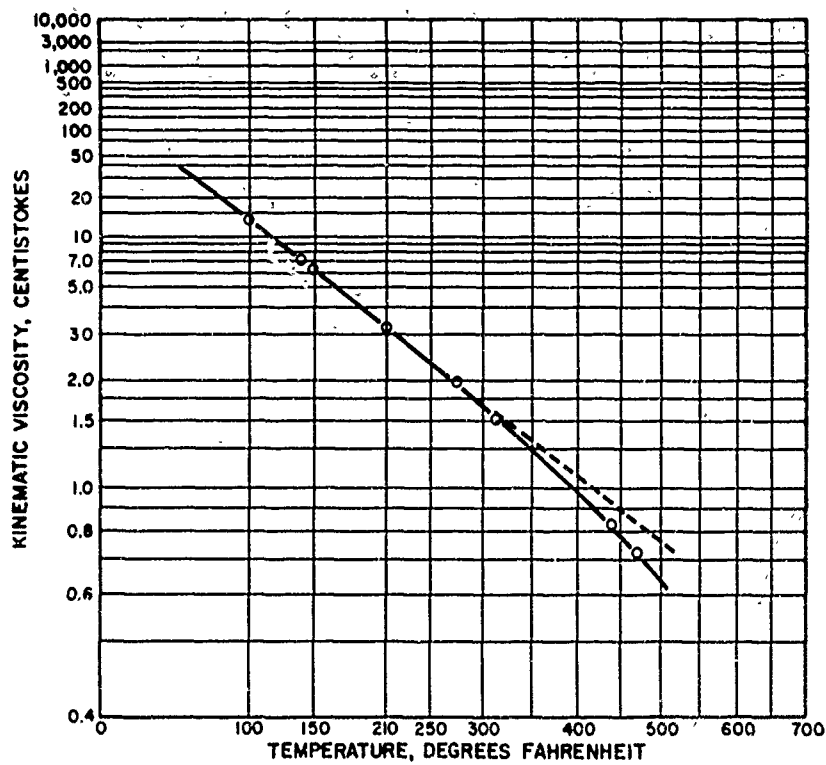


Figure 23 - Viscosity-Temperature Plot for 0-68-1

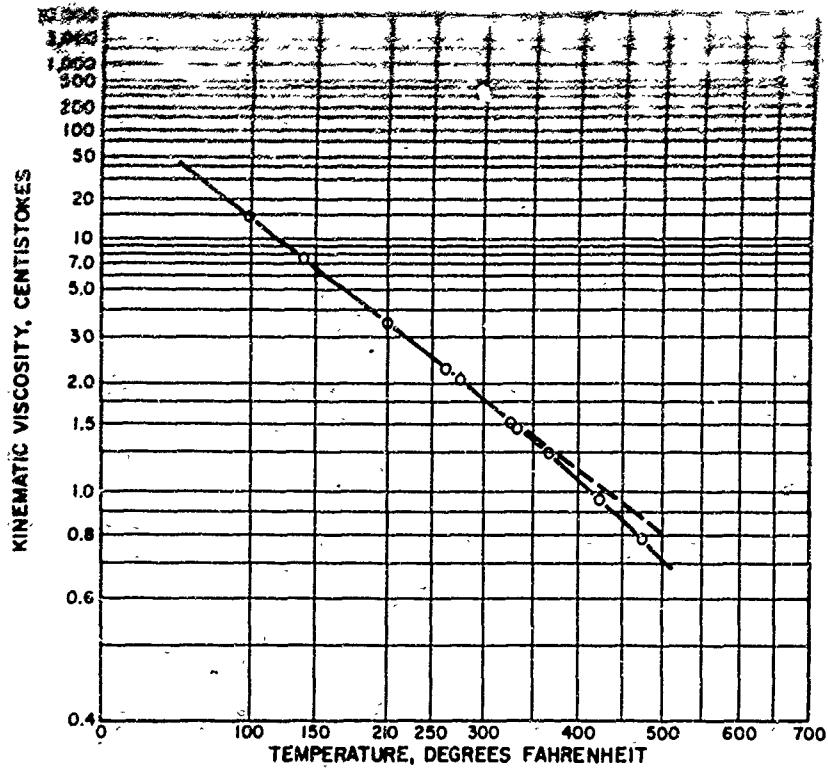


Figure 24 - Viscosity-Temperature Plot for 0-68-7

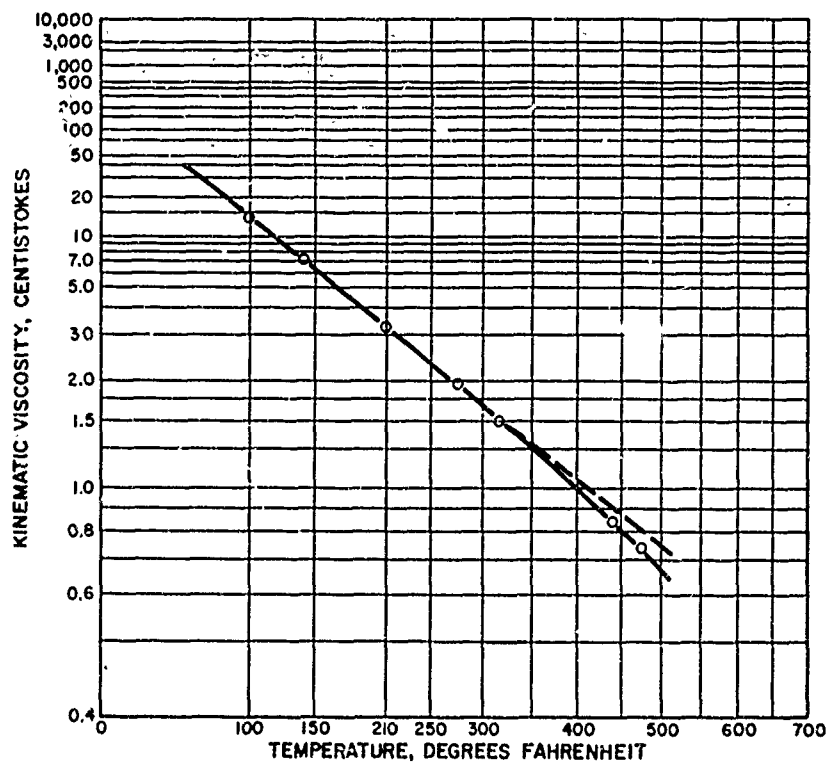


Figure 25 - Viscosity-Temperature Plot for 0-68-12

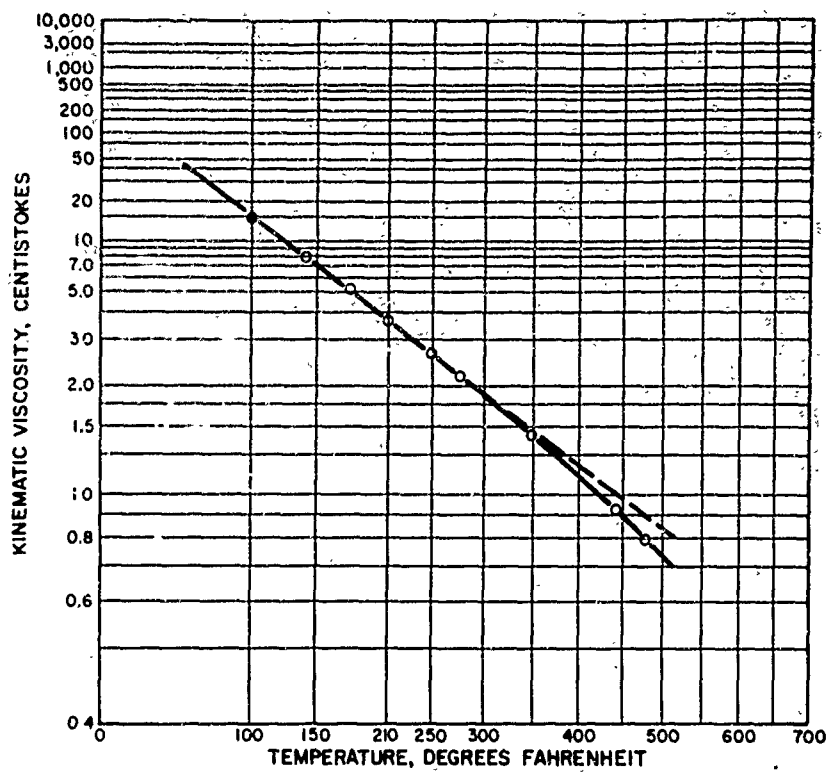


Figure 26 - Viscosity-Temperature Plot for 0-68-13

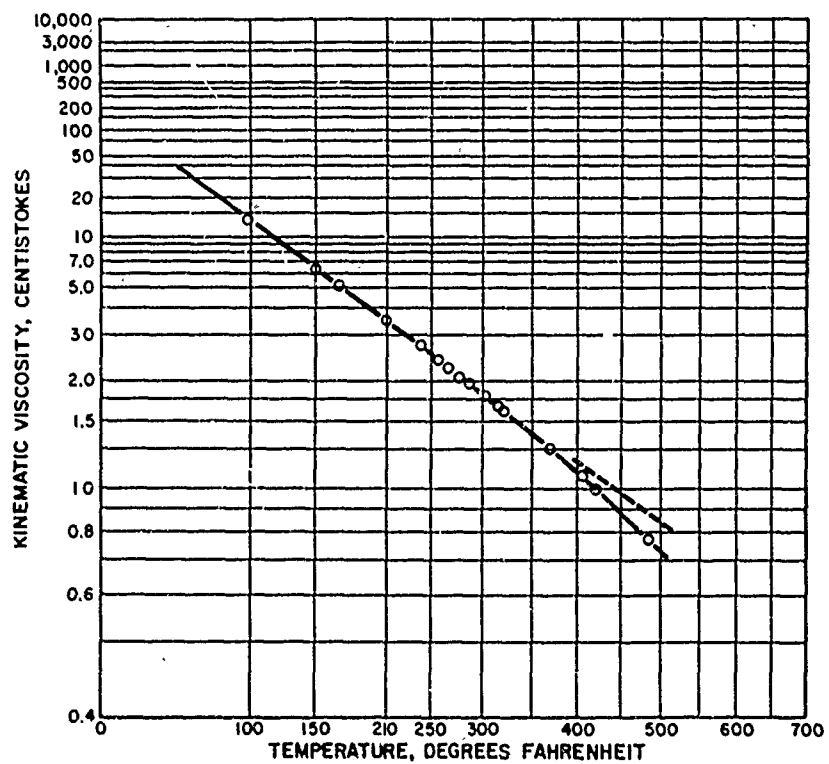


Figure 27 - Viscosity-Temperature Plot for 0-68-17

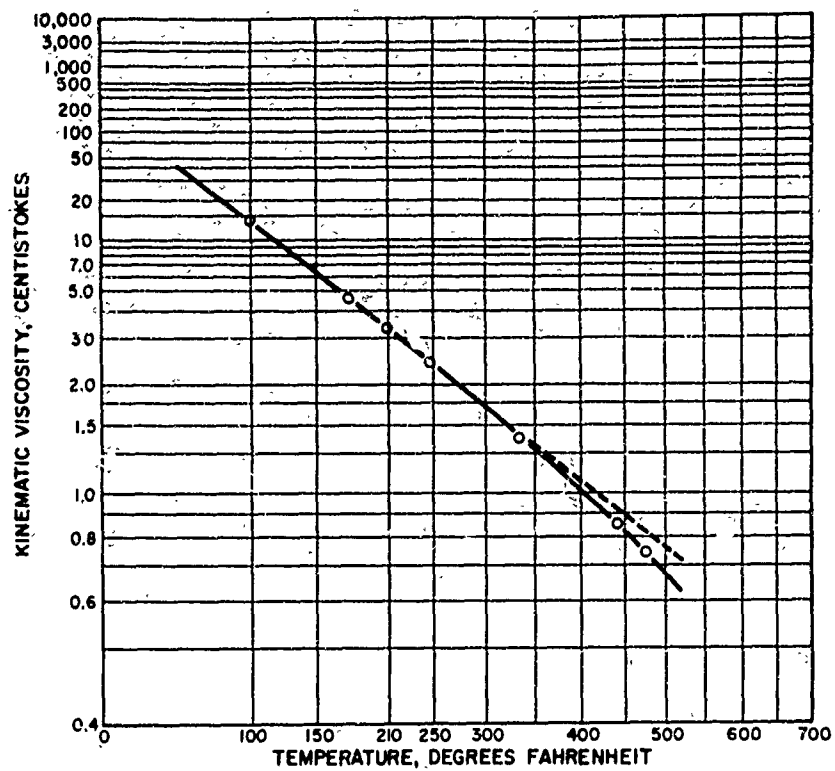


Figure 28 - Viscosity-Temperature Plot for 0-69-5

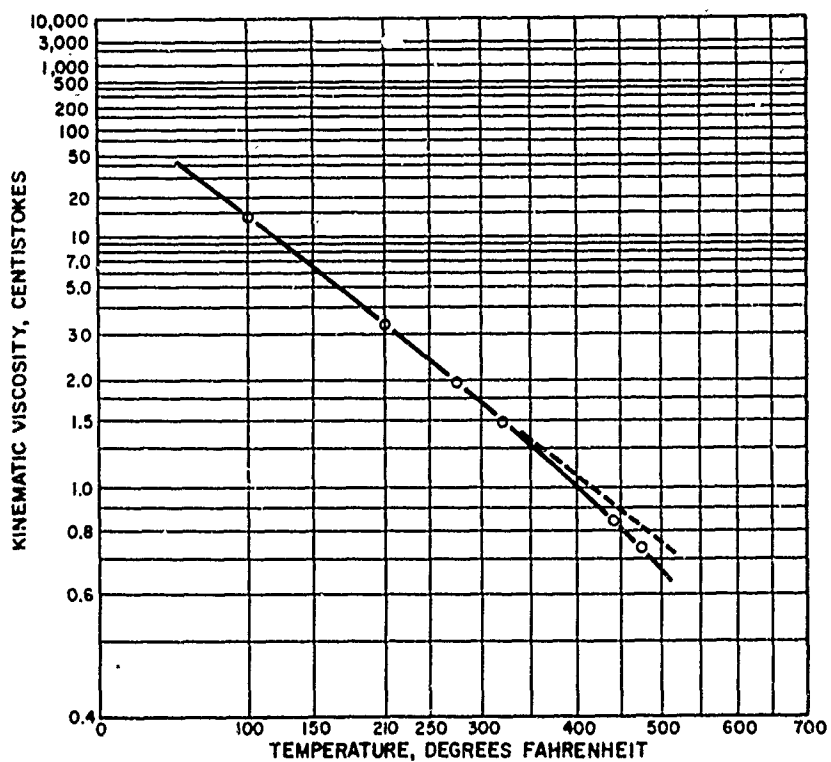


Figure 29 - Viscosity-Temperature Plot for 0-69-10

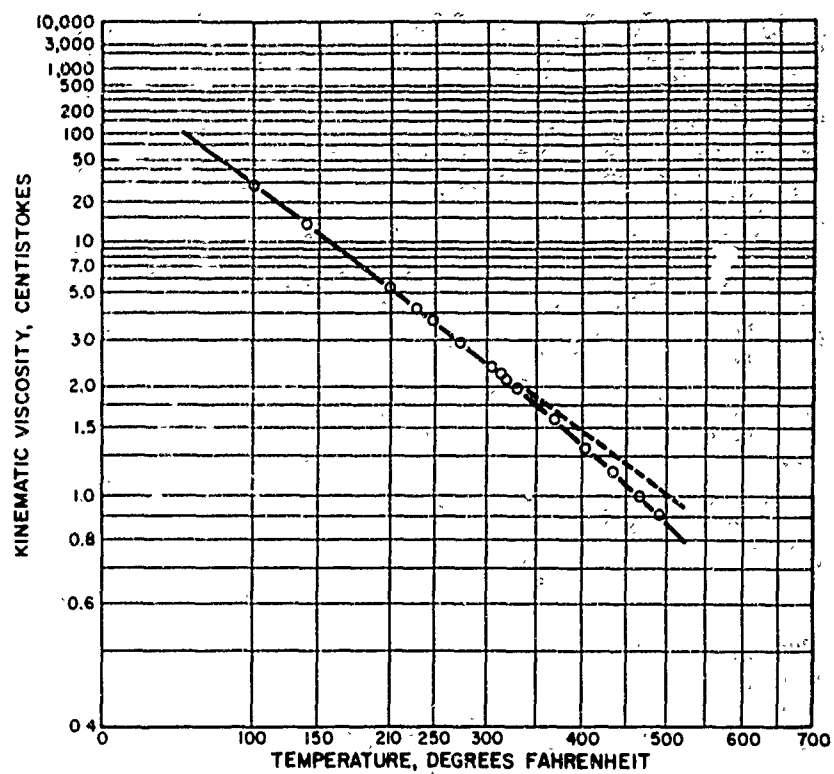


Figure 30 - Viscosity-Temperature Plot for 0-69-17

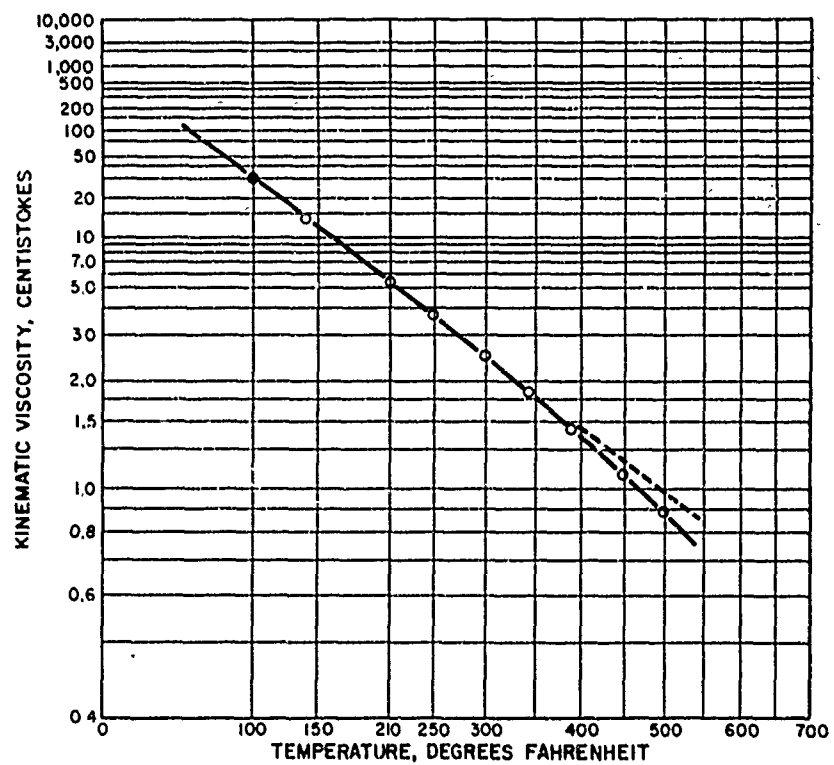


Figure 31 - Viscosity-Temperature Plot for 0-69-19

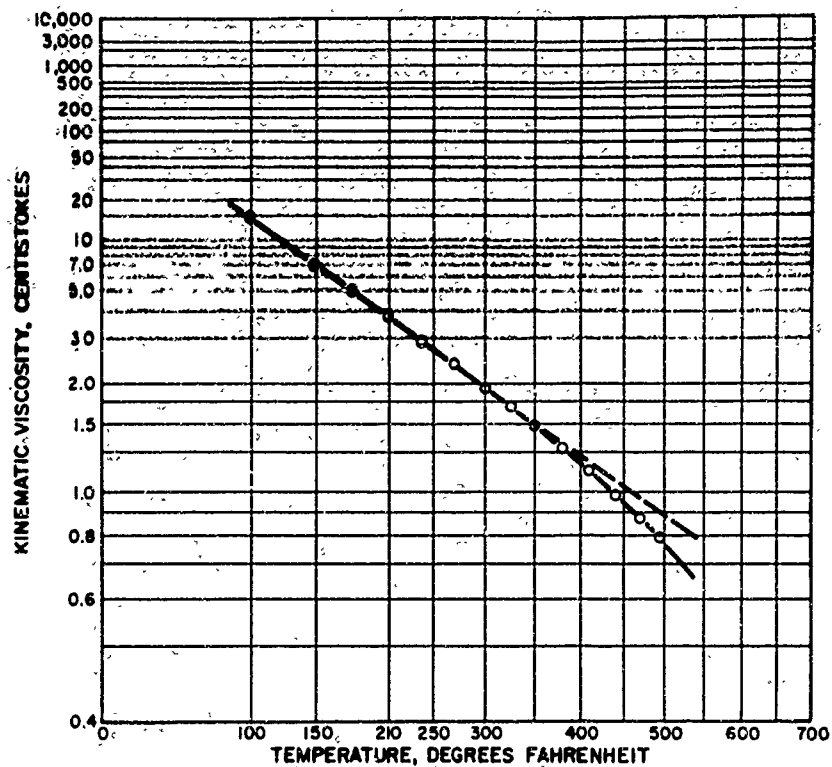


Figure 32 - Viscosity-Temperature Plot for 0-70-2

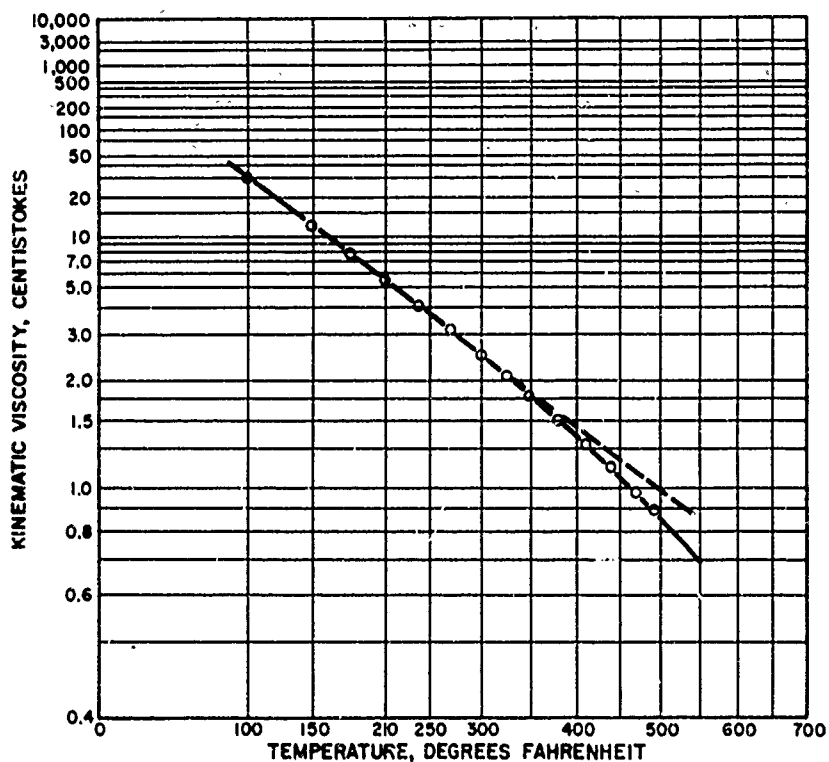


Figure 33 - Viscosity-Temperature Plot for 0-70-6

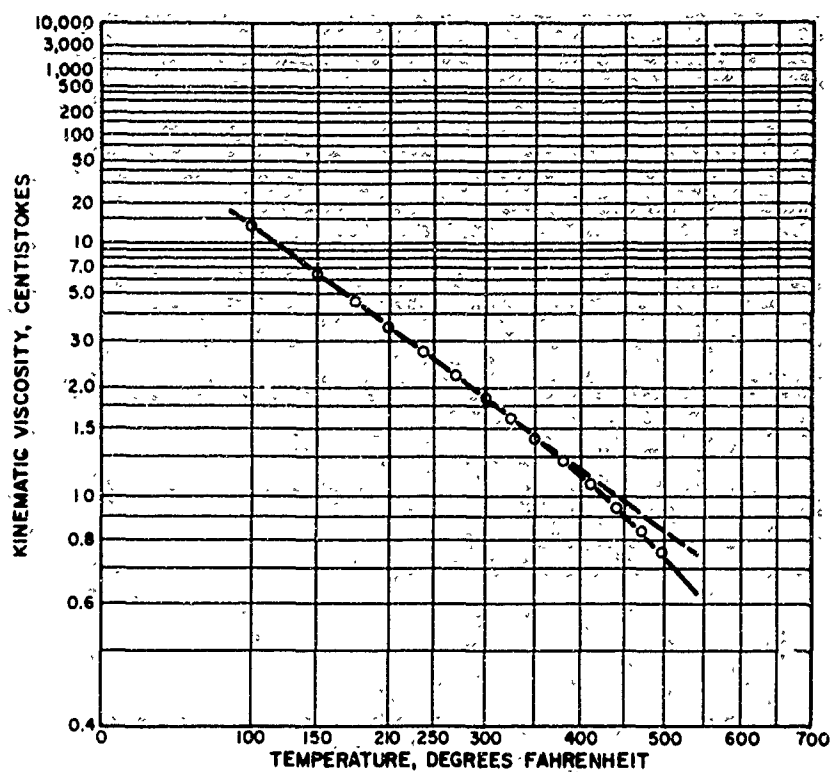


Figure 34 - Viscosity-Temperature Plot for 0-70-7

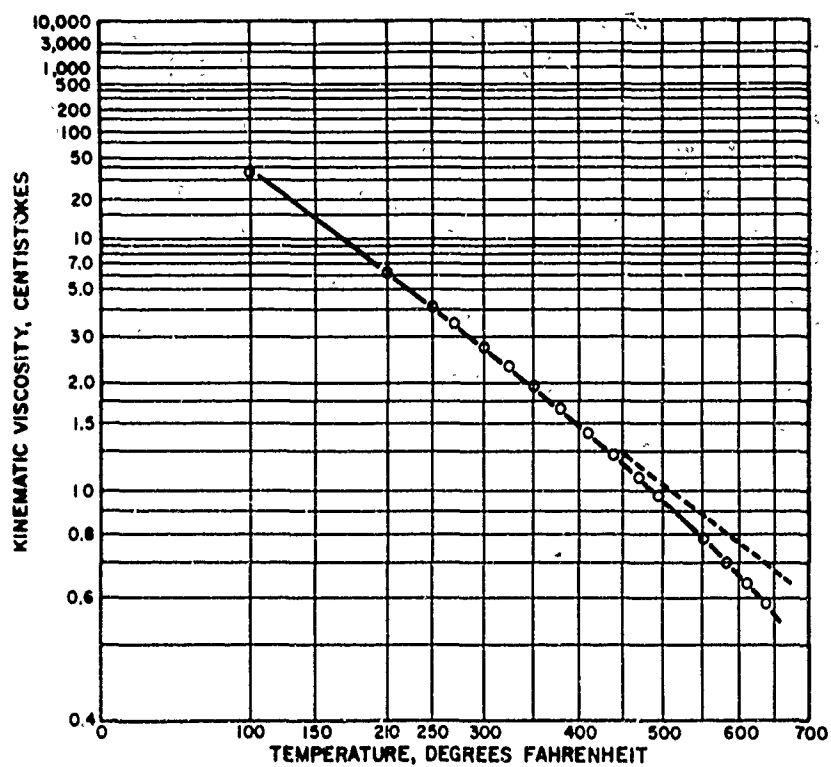


Figure 35 - Viscosity-Temperature Plot for 0-70-10

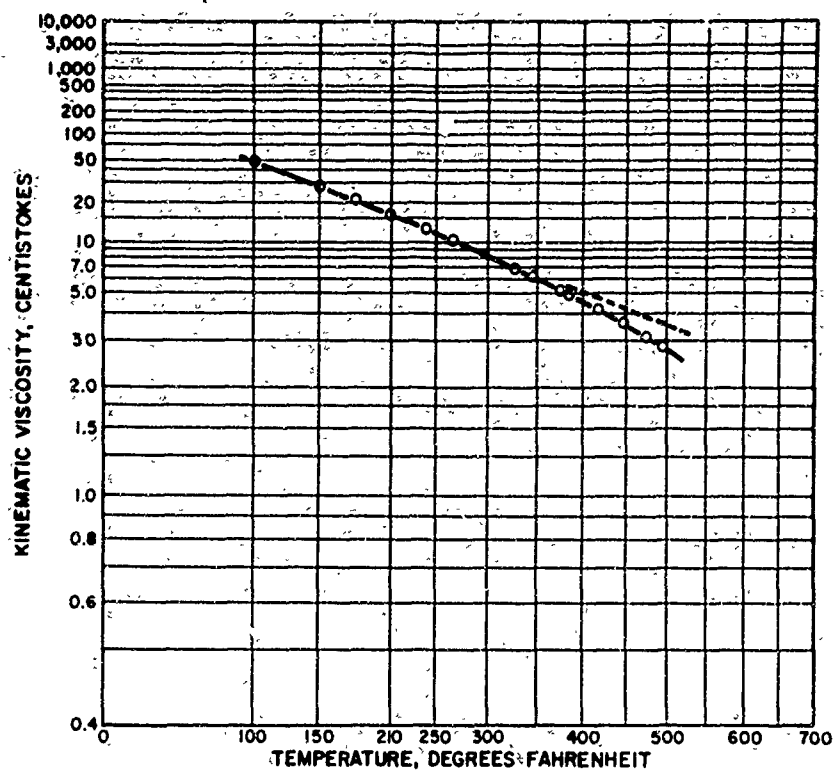


Figure 36 - Viscosity-Temperature Plot for MLO-62-1014

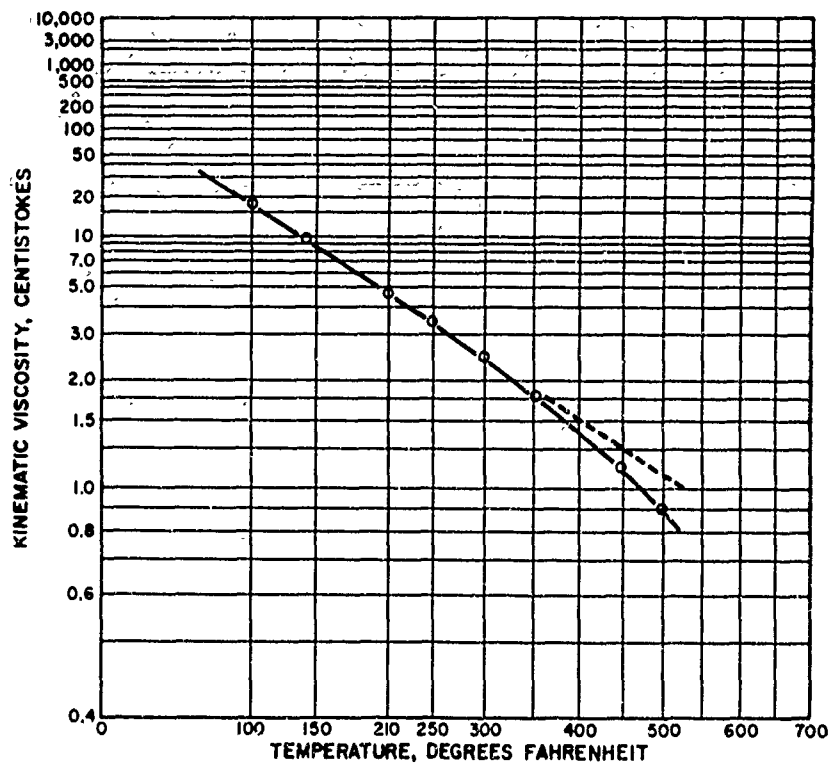


Figure 37 - Viscosity-Temperature Plot for ATL-0111

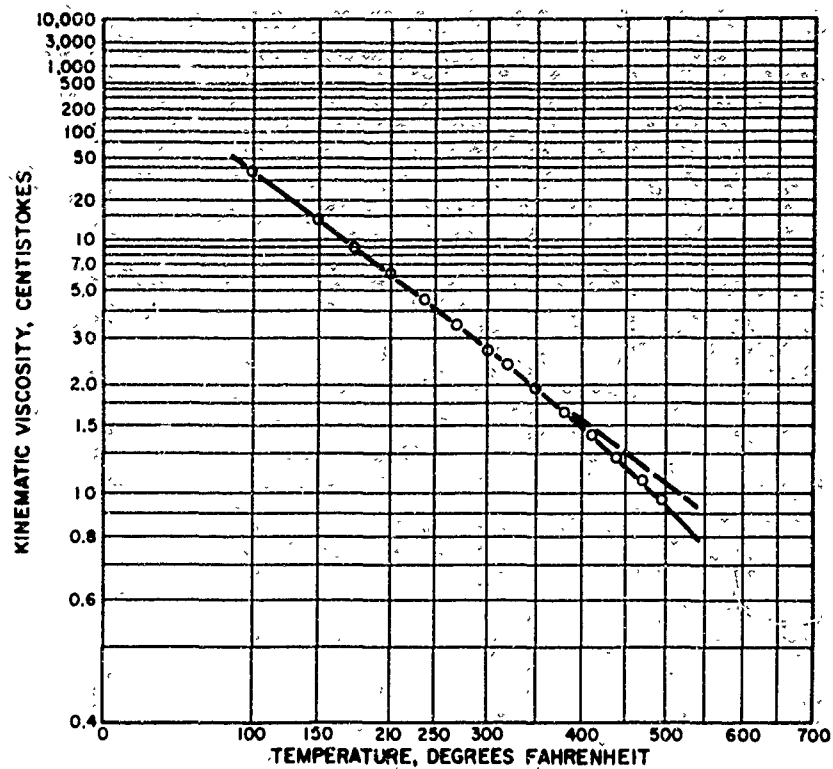


Figure 38 - Viscosity-Temperature Plot for ATL-0232

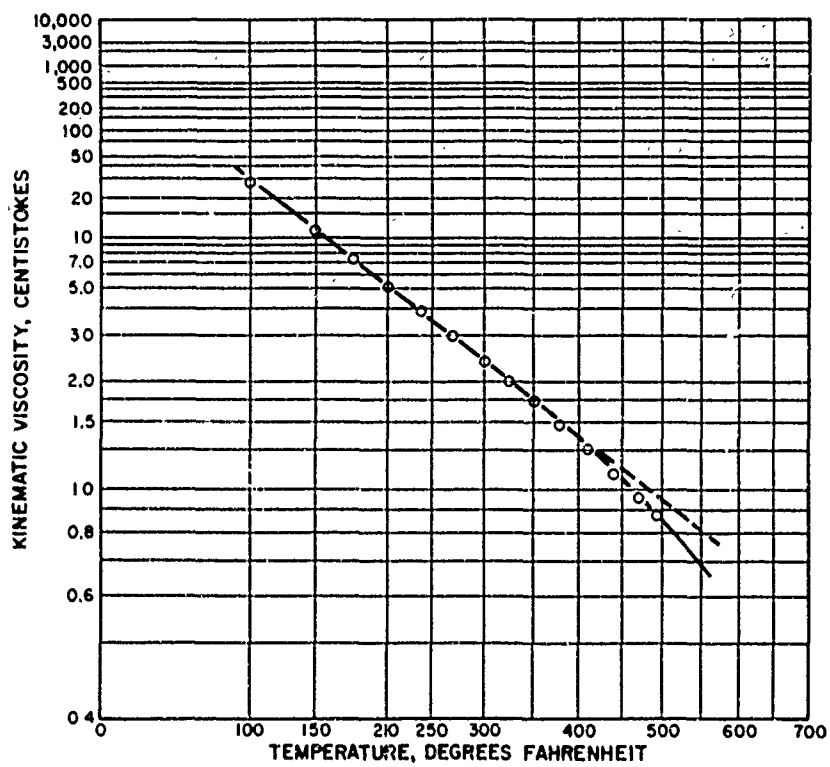


Figure 39 - Viscosity-Temperature Plot for ATL-0233

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